4.0 How EPA Developed the Tier 1 and Tier 2 IWEM Evaluations

This chapter describes how EPA developed the Tier 1 and Tier 2 IWEM evaluations using EPACMTP. Section 4.1 provides an overview of the selected EPACMTP modeling options and parameters to develop the Tier 1 and Tier 2 analyses. Section 4.2 provides a detailed discussion of the input data for Tier 1 and Tier 2.

4.1 Overview

To develop the Tier 1 and Tier 2 evaluations, we linked the EPACMTP model described in the previous chapter to a series of databases that describe WMU characteristics, hydrogeological characteristics, and constituent fate and transport data. We used EPACMTP in a Monte Carlo mode to obtain a probability distribution of model outcomes, that is, predicted concentration levels at a ground-water well located downgradient from a WMU.

In Tier 1, the Monte Carlo process reflects the nationwide variations in WMU and site conditions that might affect the impact of leachate on ground water. In Tier 2, the user is required to input a few site-specific parameters; the user may also set several more parameters to site-specific values if these data are available. If site-specific data are not available, and for the additional parameters which cannot be modified by the user, values are drawn randomly from national or regional distributions. The underlying assumption in Tier 2 is that if a site-specific parameter value is not available, the uncertainty in the value of the parameter is captured by the nationwide range in values of that parameter. The Tier 2 evaluation also has the capability to reduce the uncertainty in some of the modeling parameters by using supporting site characterization data even if the actual value of a parameter is not known. For instance, if the actual value of hydraulic conductivity in the saturated zone is unknown, but information is available about the type of subsurface environment at the site (for example, alluvial versus sedimentary rock), the Tier 2 evaluation will use this information to reduce the uncertainty in the hydraulic conductivity by selecting only hydraulic conductivity values in the Monte Carlo process that are representative of alluvial aquifers. This methodology is discussed in detail in Section 4.2.3.1.

In using a Monte Carlo modeling approach, a higher number of realizations usually leads to a more stable and more accurate result. The desire to use the most accurate result possible, however is balanced by the computational demands of running Monte Carlo simulations with a large number of realizations. Based on the results of a bootstrap analysis (see Section 3.4), we determined that performing 10,000 Monte Carlo realizations would achieve the goals for the Tier 1 and Tier 2 analysis. The Tier 1 LCTV tables which are presented in Appendix F and incorporated into the IWEM software, are based on 10,000 Monte Carlo realizations. Likewise, in a Tier 2 analysis, the IWEM software evaluation will execute 10,000 realizations of EPACMTP. We used the 90^{th} percentile of the CDF of predicted ground-water concentrations to determine LCTVs for the Tier 1 analyses and to compare directly with RGCs in Tier 2 analyses.

For each realization, EPACMTP computes a maximum average constituent exposure concentration at a well (see Section 3.0). We used the same averaging period as the exposure period upon which the corresponding RGC is based. For instance, MCLs are compared against the peak ground-water well concentration; HBNs based on carcinogenic effects are compared against the maximum 30-year well concentration, and non-cancer HBNs are compared against the maximum 7-year well concentration. For the Tier 1 and Tier 2 analyses, EPACMTP used a 10,000 year maximum time horizon to calculate ground-water well concentrations. This means that EPACMTP determined the maximum ground-water concentration occurring within a period of 10,000 years after leaching begins. This does not mean that we ran all EPACMTP simulations out to 10,000 years; in most cases the leachate plume reaches the ground-water well much sooner. However in certain cases (e.g., low infiltration rate, deep unsaturated zone, strongly sorbing constituents) it is possible that EPACMTP would predict it takes more than 10,000 years to reach the well. In these cases the concentration value returned by the model is the concentration at 10,000 years (or more exact, the average concentration up to the 10,000 year time horizon for the RGC of concern, for example, the average concentration between years 9,970 - 10,000 in the case of carcinogenic HBNs).

To enable the IWEM Tier 2 evaluation to perform the Monte Carlo analyses on common desktop computer systems, we implemented EPACMTP using a computationally efficient pseudo-3-D approximation for modeling saturated zone plume transport (see Section 3.3 of the document). The resulting computer time requirements for a Tier 2 evaluation, involving all three liner designs (no-liner, single liner, and composite liner) is approximately 3 hours per waste constituent.[4]

4.1.1 EPACMTP Modeling Options and Parameters

In Tier 1, the only required IWEM inputs are the type of WMU to be evaluated, the waste constituents present in the leachate, and the leachate concentration value for each constituent. In Tier 2, there are a small number of additional required site-specific user input parameters, as well as a number of optional site-specific user-input parameters. The required additional site-specific Tier 2 parameters are:

[4] This estimate is for a 500 MHz, Pentium-III or equivalent personal computer.

- WMU Area
- WMU Depth (for LF and SIs)
- WMU location (to select the appropriate climate parameters)

Optional site-specific Tier 2 inputs are:

- Distance to the nearest surface waterbody (for SIs)
- Depth of the base of the WMU below ground surface (LFs, WPs, and SIs)
- Operational Life of the WMU (for SIs, WPs, and LAUs)
- Sludge thickness (SI)
- Waste type (WP)
- Leakage (infiltration) rate from the WMU
- Distance to the nearest down-gradient well
- Unsaturated zone soil type
- Subsurface environment type, and/or individual values of;
  - Depth from ground surface to the water table
  - Saturated thickness of the upper aquifer
  - Hydraulic conductivity in the saturated zone
  - Regional hydraulic gradient in the saturated zone
  - Ground water pH
- Constituent-specific sorption coefficient (K_d)
- Constituent-specific (bio-)degradation rate
- Constituent-specific RGC and corresponding exposure duration

Table 4.1 summarizes the modeling options and parameters we used to developed the Tier 1 and Tier 2 analyses. Parameters that are used differently in Tier 1 versus Tier 2 are flagged as such; usually this is the case for Tier 2 parameters that the user may input as site-specific values.

IWEM parameters can be grouped into five categories: WMU infiltration and recharge, well location, soil and hydrogeology, and constituent-specific. The required site-specific parameters are <u>underlined</u> in Table 4.1. The third column in Table 4.1 indicates where you can find a detailed discussion of each parameter in this section. The *IWEM User's Guide* provides additional guidance in selecting site-specific values for these parameters.

Table 4.1 Summary of EPACMTP Options and Parameters

Modeling Element	Description or Value	Section Reference
WMU Parameters		
Waste Management Scenario	LF SI WP LAU	4.2.1
WMU Location (Nearest Climate Station)	***Tier 1***: Monte Carlo from nationwide distribution ***Tier 2***: Required site-specific user input	4.2.1.3
Leachate concentration (mg/L)	***Tier 1***: Required constituent-specific user input ***Tier 2***: Required constituent-specific user input	4.2.1.3
Operational Life (Leaching Duration) (yrs)	*LF:* Calculated inside EPACMTP; leaching continues until all waste depleted. *SI, WP & LAU:* ***Tier 1***: SI = Distribution from SI survey WP = 20 yrs LAU = 40 yrs ***Tier 2:*** Optional user input; defaults same as Tier 1	4.2.1.3
WMU Area (m^2)	***Tier 1***: Nationwide distribution from industrial WMU surveys; ***Tier 2:*** Required site-specific user input	4.2.1.3
Depth of Waste in WMU (m)	Used for LFs and SIs; not applicable in case of WP or LAU. Equivalent to ponding depth for SIs. ***Tier 1***: Nationwide distribution from industrial WMU surveys; **Tier 2:** Required site-specific user input for LF and SI	4.2.1.3
WMU Base Elevation below Ground Surface (m)	***Tier 1:*** Distribution for SI. For all other units set to 0.0 (unit base at ground surface) ***Tier 2:*** Optional user input; default = 0.0	4.2.1.3
Distance to Nearest Surface Water Body (m)	Used to evaluate water table mounding for SI units ***Tier 1:*** 360 m ***Tier 2:*** Optional user input; default = 360 m	4.2.1.3
SI sediment layer thickness (m)	Thickness of accumulated sediment (sludge)layer in SI ***Tier 1:*** 0.2 m ***Tier 2:*** Optional user input; default = 0.2 m	4.2.1.3
Waste type permeability (cm/sec)	Used for WPs only; not applicable to other WMUs ***Tier 1:*** Nationwide, uniform distribution of three waste types (low-medium-high permeability) ***Tier 2:*** Optional user input; default same as Tier 1	4.2.2.2

Table 4.1 Summary of EPACMTP Options and Parameters (continued)

Modeling Element	Description or Value	Section Reference
Infiltration and Recharge Parameters		
No Liner Infiltration (m/yr)	LF:	4.2.2.2
	Tier 1: Nationwide distribution derived using HELP model based on survey of industrial landfill locations	
	Tier 2: Optional user input; default generated using HELP model based on site location	
	SI:	
	Tier 1: Calculated by EPACMTP based on distribution of SI ponding depths	4.2.2.2
	Tier 2: Optional user input; default calculated by EPACMTP based on site-specific ponding depth	
	WP:	
	Tier 1: Nationwide distribution derived using HELP model based on survey of industrial waste pile locations	4.2.2.2
	Tier 2: Optional user input; default generated using HELP model based on site location	
	LAU:	
	Tier 1: Nationwide distribution derived using HELP model based on survey of industrial LAU locations	4.2.2.2
	Tier 2: Optional user input; default generated using HELP model based on site location	
Single Liner Infiltration (m/yr)	LF:	4.2.2.3
	Tier 1: Nationwide distribution derived using HELP model with 3 ft. clay liner and survey of industrial landfill locations	
	Tier 2: Optional user input; default generated using HELP model based on site location and 3 ft. clay liner	
	SI:	
	Tier 1: Calculated by EPACMTP based on SI ponding depth distribution and 3 ft clay liner	4.2.2.3
	Tier 2: Optional user input; default calculated by EPACMTP based on site-specific ponding depth and 3 ft clay liner	
	WP:	
	Tier 1: Nationwide distribution derived using HELP model with 3 ft. clay liner and survey of industrial waste pile locations	4.2.2.3
	Tier 2: Optional user input; default generated using HELP model based on site location and 3 ft. clay liner	
	LAU: *Not Applicable*	

Table 4.1 Summary of EPACMTP Options and Parameters (continued)

Modeling Element	Description or Value	Section Reference
Composite Liner Infiltration (m/yr)	LF: ***Tier 1:*** Nationwide distribution of reported leak detection system flow rates for composite lined units ***Tier 2:*** Optional user input; default same as Tier 1. SI: ***Tier 1:*** Calculated using Bonaparte (1989) equation for geomembrane liner using nationwide distribution of leak densities and unit-specific ponding depths; ***Tier 2:*** Optional user input; default same as Tier 1 WP: ***Tier 1:*** Nationwide distribution of reported leak detection system flow rates for composite lined units; ***Tier 2:*** Optional user input; default same as Tier 1 LAU: *Not Applicable*	4.2.2.4 4.2.2.4 4.2.2.4
Recharge Rate (m/yr)	All WMU types: ***Tier 1:*** Monte Carlo based on nationwide distribution of WMU locations and regional soil types ***Tier 2:*** Monte Carlo based on distribution of soil types and location-specific climate conditions	4.2.2.5
Soil and Hydrogeologic Parameters		
Subsurface environment	***Tier 1:*** Nationwide distribution of 13 major aquifer types associated with the locations of WMUs. ***Tier 2:*** Optional user input; default is unknown subsurface environment	4.2.3.1
Depth to ground water (m)	***Tier 1:*** Nationwide distribution, correlated with subsurface environment ***Tier 2:*** Optional user input; default derived from subsurface environment if known, otherwise national average value (5.18 m)	4.2.3.1
Soil Hydraulic Parameters: (Hydraulic conductivity; saturated water content; residual water content; moisture retention curve parameters)	Distribution of values corresponding to three major soil types (sandy loam, silt loam, and silty clay loam). Probability of occurrence of each soil type based on nationwide distribution	4.2.3.2
Soil Temperature (°C)	Assigned based on WMU location	4.2.3.2
Bulk density (kg/L)	Assigned based on selected soil type (sandy loam, silt loam, or silty clay loam)	4.2.3.2

Table 4.1 Summary of EPACMTP Options and Parameters (continued)

Modeling Element	Description or Value	Section Reference
Unsaturated Zone Percent Organic Matter	Distribution of values corresponding to three major soil types (sandy loam, silt loam, and silty clay loam). Probability of occurrence of each soil type based on nationwide distribution	4.2.3.2
Unsaturated Zone pH	Assumed to be same as saturated zone pH; nationwide distribution derived from STORET ground-water quality database	4.2.3.2
Saturated Zone Hydraulic Conductivity (m/yr)	***Tier 1:*** Nationwide distribution, correlated with subsurface environment ***Tier 2:*** Optional user input; default derived from subsurface environment if known, otherwise national average (1890 m/y)	4.2.3.3
Regional Ground water Hydraulic Gradient	***Tier 1:*** Nationwide distribution, correlated with subsurface environment ***Tier 2:*** Optional user input; default derived from subsurface environment if known, otherwise national average (0.0057 m/m)	4.2.3.1
Saturated Zone Thickness (m)	***Tier 1:*** Nationwide distribution, correlated with subsurface environment ***Tier 2:*** Optional user input; default derived from subsurface environment if known, otherwise national average (10.1 m)	4.2.3.1
Saturated Zone Porosity	Derived from nationwide distribution of mean aquifer particle diameter	4.2.3.3
Saturated Zone Bulk Density (kg/L)	Derived from saturated zone porosity	4.2.3.3
Saturated Zone pH	Nationwide distribution derived from STORET water quality database	4.2.3.3
Saturated Zone Fraction Organic Carbon	Nationwide distribution derived from STORET water quality database	4.2.3.3
Saturated Zone Temperature (°C)	Assigned based on WMU location	4.2.3.3
Constituent Fate and Transport Parameters		
Molecular Diffusion Coefficient (m^2/yr)	Accounts for constituent transport via diffusion in soil and ground water. Calculated from constituent-specific free-water diffusion coefficients	3.2, 3.3

Table 4.1 Summary of EPACMTP Options and Parameters (continued)

Modeling Element	Description or Value	Section Reference
Transformation Parameters • Hydrolysis Rate (yr^{-1}) • (Bio-)degradation (yr^{-1})	Tier 1 and Tier 2 account for hydrolysis transformation reactions using constituent-specific hydrolysis rate constants. Other types of (bio-)degradation processes can be entered as optional Tier 2 constituent specific parameters	4.2.4.1
Sorption Parameters • Organic Carbon Partition Coefficient (kg/L) • Soil-Water Partition Coefficient (kg/L)	For organic constituents, equilibrium sorption is taken into account via constituent-specific organic carbon partition coefficients; for metals, effective equilibrium partition coefficients are generated using the MINTEQA2 geochemical speciation model	4.2.4.3
Well Location Parameters		
Downgradient Distance from WMU (m)	***Tier 1:*** Set to 150 meters ***Tier 2:*** Optional user input (limited to 1600 meters); default same as Tier 1	4.2.5
Transverse Distance from Plume Centerline (m)	Well always on centerline of plume, transverse distance is 0.0	4.2.5
Depth of Well Intake (m)	Uniform distribution from 0 - 10 m below water table	4.2.5

4.2 EPACMTP Input Parameters Used to Develop Tier 1 and Tier 2 Tools

This section describes the parameters we used to develop the Tier 1 and Tier 2 tools, including their data sources, methodologies, and values. Appendix C provides detailed tables of Tier 1 parameter values. Section 4.2.1 describes WMU parameters. Section 4.2.2 describes the infiltration and recharge parameters. Section 4.2.3 describes the unsaturated zone and saturated zone parameters. Section 4.2.4 describes constituent-specific chemical fate parameters. Section 4.2.5 describes the well location parameters, and Section 4.2.6 describes the screening procedures we implemented in the Monte Carlo analysis to eliminate physically unrealistic parameter combinations.

4.2.1 WMU Parameters

4.2.1.1 WMU Types

IWEM simulates four different types of WMUs. Each of the four IWEM units reflects waste management practices that are likely to occur at industrial Subtitle D facilities. The WMU can be a LF, a WP, a SI, or a LAU. The latter is also sometimes called a land treatment unit. The four WMU types are represented graphically in Figure 4.1. In developing the IWEM tools, we assumed all units contained only one type of waste so that the entire capacity of the WMU is devoted to a single waste.

- **Landfill (LF).** IWEM only considers closed LFs. A closed LF is assumed to have an 2-foot soil cover and one of three liner types: no-liner; a single clay liner; or a composite liner. The LF is filled with waste during the unit's operational life. Upon closure of the LF, the waste is left in place, and a final soil cover is installed. The starting point for the simulation is at the time when the LF is closed, i.e., the unit is at maximum capacity. The release of waste constituents into the soil and ground water underneath the LF is caused by dissolution and leaching of the constituents due to precipitation which percolates through the unit. The type of liner that is present controls, to a large extent, the amount of leachate which is released from the unit. We modeled LFs as a permanent WMU, with a rectangular footprint and a uniform depth. We did not simulate any loss process that may occur during the unit's active life (for example, due to leaching, volatilization, runoff or erosion, or biochemical degradation. We modeled the leaching of waste constituents from LFs as a depleting source scenario. In the depleting source scenario, the WMU is considered permanent and leaching continues until all waste that is originally present has been depleted. In IWEM Tier 1 and Tier 2, the magnitude of the initial leachate concentration is a model input; the rate of depletion is calculated internally in EPACMTP (*see EPACMTP Technical Background Document)*.[5] The leachate concentration value which is used an IWEM input is the expected initial leachate concentration, when the waste is 'fresh'.

[5] In EPACMTP's finite source module for LFs, the rate of depletion is a function of the ratio between the waste concentration (C_W) and the leachate concentration (C_L). In IWEM, we set this ratio to a constant, protective value of C_w/C_L = 10,000.

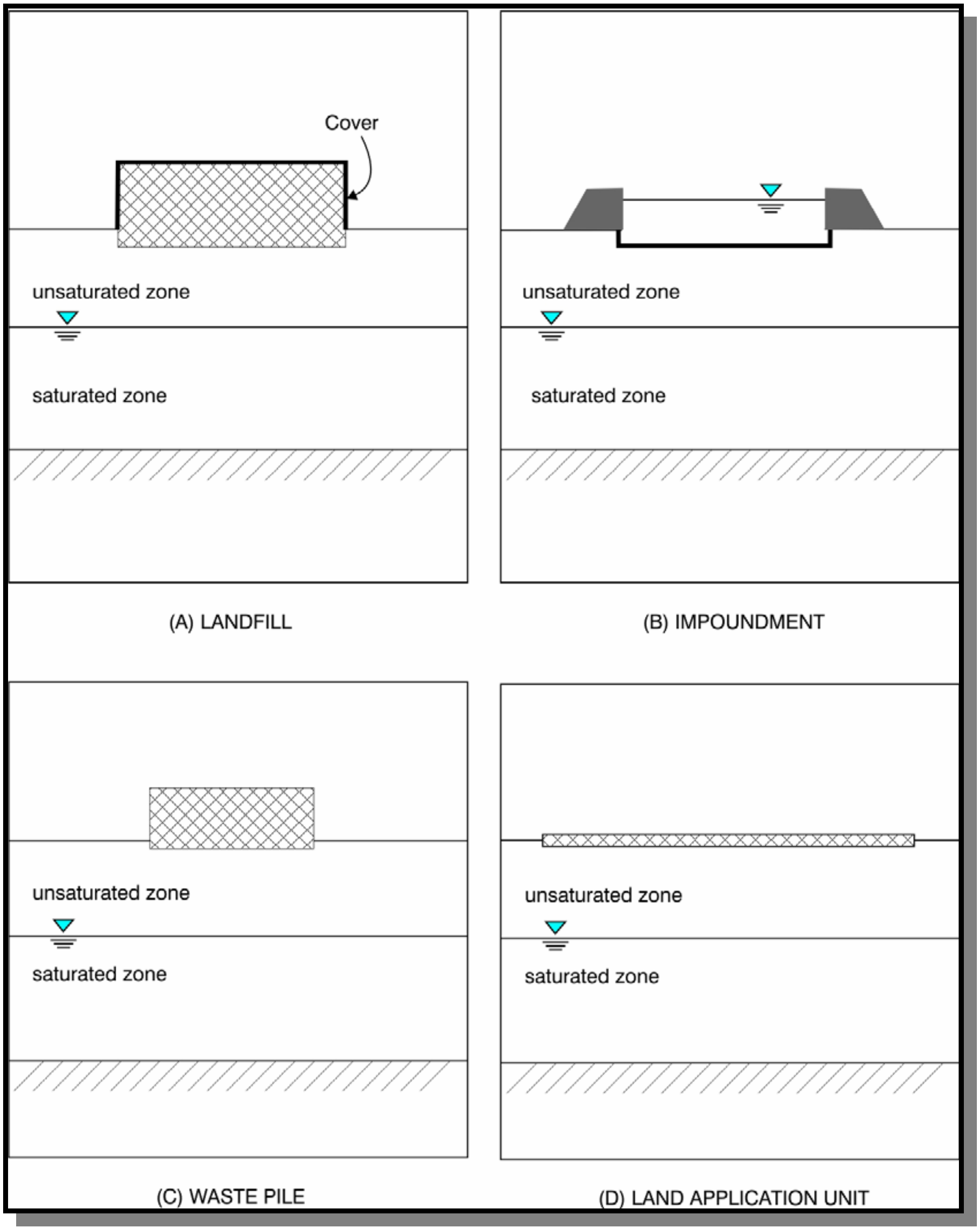

Figure 4.1 WMU Types Modeled in IWEM.

- **Waste Pile (WP).** IWEM models WPs as temporary sources used for storage of solid wastes. Due to their temporary nature, they typically will not be covered. IWEM allows liners to be present, similar to LFs. In Tier 1 analyses, IWEM assumes that WPs have a finite operational life after which the WP is removed. In IWEM, we modeled WPs as a pulse-type source, with pulse duration equal to the unit's operating life.

- **Surface Impoundment** (SI). In IWEM, SIs are ground level or below-ground level, flow-through units, which may be unlined, have a single clay liner, or have a composite clay-geomembrane liner. Release of leachate is driven by the ponding of water in the impoundment, which creates a hydraulic head gradient with the ground water underneath the unit. At the end of the unit's operational life, we assume there is no further release of waste constituents to the ground water (that is, clean closure from the SI). We modeled SIs as pulse-type sources; leaching occurs at a constant leachate concentration over a fixed period of time which is equal to the unit's operating life. We also assume a constant ponding depth (depth of waste water in SI) during the operational life.

- **Land Application Unit (LAU)**. LAU (or land treatment units) are areas of land which receive regular applications of waste that can be either tilled or sprayed directly onto the soil and subsequently mixed with the soil. IWEM models the leaching of wastes after tilling with soil. IWEM does not account for the losses due to volatilization during or after waste application. LAUs are modeled in IWEM as a constant pulse-type leachate source, with a leaching duration equal to the unit's operational life. We evaluated only the no-liner scenario for LAUs because liners are not typically used at this type of unit.

4.2.1.2 WMU Data Sources

In order to develop WMU parameters for IWEM, we used data from two nationwide EPA surveys of industrial Subtitle D WMUs. Data for LFs, WPs, and LAUs were obtained from an EPA survey of industrial D facilities conducted in 1986 (U.S. EPA, 1986). The survey provides a statistical sample design based set of observations of site specific areas, volumes and locations for industrial Subtitle D facilities in the United States. In the following description of WMU data, we will refer to this survey as the "*1986 Subtitle D survey.*" Data for SIs were obtained from a recent Agency survey of industrial SIs (U.S. EPA, 2001). We will refer to this survey as the "*Surface Impoundment Study.*"

Landfills

The *1986 Subtitle D survey* provided LF data consisting of 824 observations of facility locations, area, number of units in the facility, facility design capacity, total remaining facility capacity, and the relative weight of each facility. The relative weight was assigned based on the total number of employees working at the facility and reflects the quantity of the waste managed in that facility.

We screened the LF data by placing constraints on the WMU depth and volume to eliminate unrealistic observations. The WMU depth, calculated by dividing the unit capacity by its area, was constrained to be either greater than or equal to 2 feet (0.67m), or less than or equal to 33 feet (10m). In addition, the LF volume was constrained to be greater than the remaining capacity. Ten area observations were reported missing and none were screened. Ninety-one volume observations were reported missing and 232 additional volume observations were screened.

In cases where the WMU depth or remaining capacity constraints were violated, we replaced the observed unit volume by generating a random realization from the volume probability distribution conditioned on area assuming that the unit area value was more likely to be correctly reported. The joint distribution was derived from the non-missing unit area/volume pairs that met the unit depth and remaining capacity constraints and was assumed to be lognormal. Missing values were generated from the joint area/volume probability if both the area and volume were missing, and from the corresponding conditional distribution if only one of the two values was missing. Final depth values were calculated by dividing the unit volume by the area.

Figure 4.2 shows the geographic locations of LF WMUs used in developing the Tier 1 and Tier 2 tools. A summary of the descriptive statistics of the LF parameters is provided in Appendix C; additional detailed data is provided in the *EPACMTP Parameters/Data Background Document* (U.S. EPA, 2002b).

Figure 4.2 Geographic Locations of Landfill WMUs.

Surface Impoundments

The IWEM tools incorporate SI parameters from EPA's recent 5-year study of nonhazardous (Subtitle D) industrial SIs (U.S. EPA, 2001) in the United States. The *Surface Impoundment Study* is the product of a national survey of facilities that operate non-hazardous industrial waste SIs. We used information in the *Surface Impoundment Study* to create a database of SI characteristics comprising 503 SI units located at 143 facilities throughout the United States.

The *Surface Impoundment Study* provided data on impoundment locations, area, operating depths (depth of ponding in the impoundment), depth of the SI base below the ground surface, operational life of the impoundment, and proximity of the impoundment to a surface water body.

Figure 4.3 shows the geographic locations of the 143 SI facilities used from the *Surface Impoundment Study*. Due to the scale of this map, the individual units at each facility are not shown. A summary of the descriptive statistics of the SI unit parameters is provided in Appendix C; additional detailed data are provided in the *EPACMTP Parameters/Data Background Document* (U.S. EPA, 2002b).

Figure 4.3 Geographic Locations of Surface Impoundment WMUs.

Waste Piles

The *1986 Subtitle D survey* included 847 WP facilities with data on facility area, number of units, and the total amount of waste placed in the facility (waste volume) in 1985. We obtained unit values by dividing the facility values by the number of units in the facility. No screening constraints were placed on the WP data other than setting the 114 facility areas and the 30 facility waste volumes reporting zero values to 0.005 acres (20 m^2) and 0.005 mega-tons (Mton), respectively.

Thirty waste volume observations were reported missing. No area observations were reported missing. We replaced missing volume values by random realizations from the probability distribution of volume conditioned on area. The conditional distribution was assumed to be lognormal and was derived from the non-missing unit area/volume pairs.

Figure 4.4 shows the geographic locations of WP WMUs used in developing the Tier 1 and Tier 2 tools. A summary of the descriptive statistics of the WP parameters is provided in Appendix C; additional detailed data is provided in the *EPACMTP Parameters/Data Background Document* (U.S. EPA, 2002b).

Figure 4.4 Geographic Locations of Waste Pile WMUs.

Land Application Units

The *1986 Subtitle D survey* included 352 LAU facilities, with data on location, area, number of units in each facility, and the total amount of waste managed (waste volume) in 1985. We obtained unit values obtained by dividing the facility values by the number of units in the facility. We screened the LAU data by constraining waste application rates to be less than 10,000 tons/acre/year to eliminate unrealistic values. The application rate was calculated by dividing the waste managed in 1985 by the site acreage. (The upper bound was derived by assuming a maximum application rate of 200 dry tons/acre/year with a 2% solids content).

Eight waste volume observations were reported missing; twelve were screened out due to the application rate constraint. No area observations were reported missing and none were screened. As in the case of WPs, areas and volumes reported as zero were replaced with lower bounds. Three reported zero areas and nine reported zero waste volumes were set to 0.005 acres (20 m^2) and 0.005 Mton, respectively.

We replaced missing and screened values by random realizations from the joint area/volume probability distribution or the corresponding marginal distributions depending on whether both or only one of either the waste volume or area values were missing or screened. The joint distribution was assumed to be lognormal and was derived from the non-missing unit area/volume pairs that met the unit depth constraint.

Figure 4.5 shows the geographic locations of LAU WMUs used in developing the Tier 1 and Tier 2 tools. A summary of the descriptive statistics of the LAU parameters is provided in Appendix C; additional detailed data are provided in the *EPACMTP Parameters/Data Background Document* (U.S. EPA, 2002b).

Figure 4.5 Geographic Locations of Land Application Unit WMUs.

4.2.1.3 WMU Parameters Used in Developing the Tier 1 and Tier 2 Tools

This section discusses the individual WMU-related parameters used in the IWEM modeling for Tier 1 and Tier 2. In most cases, the Tier 1 parameters are described by nationwide probability distributions. Appendix C provides a summary of the parameter distributions for each WMU type. With the exceptions noted in the following sections, these same distributions are used as the defaults in Tier 2.

Waste Leachate Concentration (mg/L)

Values of leachate concentration for all constituents of concern are required Tier 1 and Tier 2 input parameters. This parameter can be an actual measured value, or it can be an expected or estimated value. The user-provided leachate concentration values are the basis for IWEM's determination of the minimum protective liner design.

The Tier 1 software compares user-supplied leachate concentration values against each constituent's aqueous solubility. If the user input value exceeds the aqueous solubility of that constituent in the IWEM data base, IWEM will display a warning message. A leachate concentration value above the aqueous solubility value may indicate a number of conditions: (1) a measurement error, or (2) a case outside the validity of the EPACMTP fate and transport model. The model is designed to simulate transport of dissolved aqueous phase constituents, and therefore, the solubility is the theoretical maximum concentration value that may occur. However, IWEM will not reject user supplied leachate concentration values.

WMU Location

We obtained WMU locations from the *1986 subtitle D survey* and the *2001 Surface Impoundment Study*, respectively. The WMU locations are shown in Figures 4.2 - 4.5. In developing the Tier 1 and Tier 2 evaluations, we used information on WMU locations to assign appropriate site-based climate and hydrogeological parameter values to each location in the WMU database. Location-specific climate data from 102 climate stations were used to develop infiltration and recharge rates using the HELP model for unlined and single-lined WMUs (see Section 4.2.2), and to determine soil and aquifer temperature in order to calculate hydrolysis transformation rates (see Section 4.2.4). We also used information on WMU locations to assign location-specific soil and aquifer hydrogeological parameter values (see Section 4.2.3). In Tier 2, the WMU location is a required site-specific user input value that is needed by IWEM to assign the appropriate climate-related parameter values.

WMU Area (m²)

This parameter reflects the footprint area of the WMU (that is, length by width). Tier 1 values were obtained from EPA's *1986 Subtitle D Survey* and the *Surface Impoundment Study*. The WMU footprint area is a required site-specific user-input value for a Tier 2 evaluation. This parameter represents the total surface area over which infiltration and leachate enter the subsurface.

WMU Waste Depth (m)

The WMU waste depth is used for LF and SI simulations. This parameter is not used for WPs or LAUs. In the case of LFs, this parameter represents the average waste thickness in the LF at closure. EPACMTP uses the waste depth as one of the parameters to calculate the LF source depletion rate (see *EPACMTP Technical Background Document*; U.S. EPA, 2002a). The Tier 1 evaluation is based on a nationwide distribution of LF depths obtained from the *1986 Subtitle D survey*. In Tier 2, the user is required to provide a site-specific value.

For SIs, the waste depth is equal to the ponding depth, or average depth of free liquid in the impoundment. The SI ponding depth represents the hydraulic head that drives leakage of water from the SI; EPACMTP uses this parameter in order to calculate SI infiltration rates (see Section 3.1.2). The Tier 1 evaluation is based on a nationwide distribution of SI ponding depths obtained from the *2001 Surface Impoundment Study*. In Tier 2, this is a required site-specific user input parameter.

Surface Impoundment Sediment (Sludge) Layer Thickness (m)

This parameter is applicable to SIs only and represents the average thickness of accumulated sediment (sludge) deposits on the bottom of the impoundment. This layer of accumulated sediment is different from an engineered liner underneath the impoundment, but its presence will serve to restrict the leakage of water from an impoundment, especially in unlined units. EPACMTP uses this parameter to calculate the rate of infiltration from unlined and single lined SIs. The EPACMTP SI infiltration module is described in Section 3.1, with a detailed description in the *EPACMTP Technical Background Document* (U.S. EPA, 2002a).

To model SIs, we assumed that the accumulated sediment consists of two equally thick layers, an upper unconsolidated layer and a lower consolidated layer ('filter cake') that has been compacted due to the weight of the sediment above it, and therefore has a reduced porosity and permeability. In Tier 1, we used a total (unconsolidated + consolidated) sediment layer thickness of 0.2 meters. In Tier 2, this is an optional site-specific user input parameter, with a default value of 0.2 m.

Depth of the WMU Base Below Ground Surface (m)

This parameter represents the depth of the base of the unit below the ground surface, as schematically depicted in Figure 4.6. The depth of the unit below the ground surface reduces the travel distance through the unsaturated zone before leachate constituents reach ground water. The SI characterization data from the EPA's 2001 *Surface Impoundment Study* provided unit-specific data for SIs that we used in the Tier 1 modeling. This parameter was not included in the EPA's 1986 *Industrial Subtitle D Survey* of LFs, WPs, and LAUs. For the Tier 1 analyses of these types of WMUs, we set this parameter to zero, which is equivalent to assuming the base of the unit is level with the ground surface.

In Tier 2, this parameter is an optional site-specific user input parameter, with a default value of zero. If a non-zero value is entered at Tier 2, IWEM will verify that the entered value, in combination with the depth to the water table, and magnitude of the unit's infiltration rate, does not lead to a physically infeasible condition (e.g., water table mound height above the ground surface or above the level of the waste liquid in an impoundment) in accordance with the infiltration screening methodology presented in Section 4.2.6.

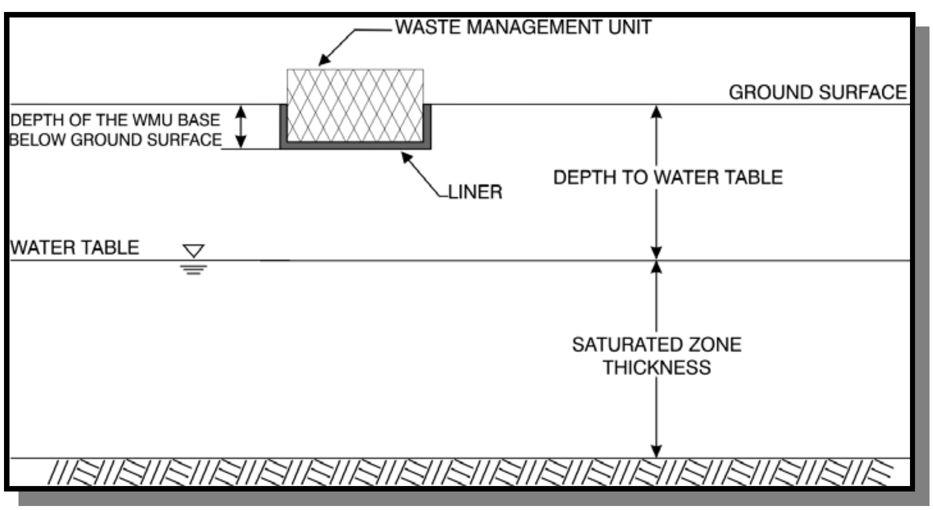

Figure 4.6 WMU with Base Elevation below Ground Surface.

Operational Life (Duration of Leaching Period) (yr)

For LFs, IWEM determines the duration of the leaching period internally, as a function of the amount of waste in the unit at closure and IWEM does not use an operational life. Because WPs, SIs and LAUs are modeled as finite duration pulse sources, we assumed the duration of the leaching period is equal to the unit's operational life.

In Tier 1, we determined unit-specific operational lives for SI, from information in the *Surface Impoundment Study* on present age of the unit and the planned closing date. If this information was missing, we assigned an operational life of 50 years. For WPs and LAUs, the 1986 *Industrial Subtitle D Survey* did not provide information on operational life. We assigned a life of 20 years for WPs and 40 years for LAUs.

In Tier 2, the operational life is an optional site-specific user input parameter for SIs, WPs, and LAUs. Tier 2 default values for this parameter are as follows:

- LAU = 40 years
- WP = 20 years
- SI = 50 years

Distance to Nearest Surface Water Body (m)

For SIs, IWEM uses information on the distance to the nearest permanent surface water, (that is, a river, pond or lake), in the infiltration screening procedure presented in Section 4.2.6. In Tier 1, we used reported data from the EPA's *Surface Impoundment Study* to assign a distance value to each SI unit in the national database. The data from the *Surface Impoundment Study* indicated a distribution of values with a range of 30 to 5,000 meters (3.1 miles), and a median value of 360 meters (see Appendix C).

In Tier 2, this parameter is an optional site-specific user input. Because the exact distance may not be known in many cases, the input is in terms of whether or not there is surface water body within 2,000 meters of the unit. If a surface water body is present within 2,000 meters, IWEM uses the median value of 360 meters as a default. If there is no water body within 2,000 meters, IWEM will use a value of 5,000 meters in its calculations.

4.2.2 Infiltration and Recharge Rates

IWEM requires the input of the rate of downward percolation of water and leachate through the unsaturated zone to the water table. The model distinguishes between two types of percolation, infiltration and recharge:

- **Infiltration** (WMU leakage rate) is defined as water percolating through the WMU – including a liner if present – to the underlying soil.

- **Recharge** is water percolating through the soil to the aquifer outside the WMU.

Infiltration is one of the key parameters affecting the leaching of waste constituents into the subsurface. For a given leachate concentration, the mass of constituents leached is directly proportional to the infiltration rate. In the IWEM Tier 1 and Tier 2 analyses, selecting different liner designs directly correlates to changing the infiltration rate; more protective liner designs reduce leaching by decreasing the rate of infiltration.

In contrast, recharge introduces pristine water into the aquifer. Increasing recharge therefore tends to result in a greater degree of plume dilution and lower constituent concentrations. High recharge rates may also affect the extent of ground-water mounding and ground-water velocity. The recharge rate is independent of the type and design of the WMU; rather it is a function of the climatic and hydrogeological conditions at the WMU location, such as precipitation, evapotranspiration, surface run-off, and regional soil type.

We used several methodologies to estimate infiltration and recharge. We used the HELP model (Schroeder et al, 1994) to compute recharge rates for all units, as well as infiltration rates for LAUs, and for LFs and WPs with no-liner and single-liner designs. For LFs and WPs, composite liner infiltration rates were compiled from leak-detection-system flow rates reported for actual composite-lined waste units (TetraTech, 2001).

For unlined and single-lined SIs, infiltration through the bottom of the impoundment is calculated internally by EPACMTP, as described in Section 3.1 of this document. For composite-lined SIs, we used the Bonaparte (1989) equation to calculate the infiltration rate assuming circular (pin-hole) leaks with a uniform leak size of 6 mm^2, and using the distribution of leak densities (number of leaks per hectare) assembled from the survey of composite-lined units (TetraTech, 2001).

Tables 4.2 through 4.5 summarize the liner assumptions and infiltration rate calculations for LFs, WPs, SIs, and LAUs. The remainder of Section 4.2.2 provides background on how we used the HELP model in conjunction with data from climate stations across the United States to develop nationwide recharge and infiltration rate distributions and provides detailed discussion of how we developed infiltration rates for different liner designs for each type of WMU.

4.2.2.1 Using the HELP Model to Develop Recharge and Infiltration Rates

The HELP model is a quasi-two-dimensional hydrologic model for computing water balances of LFs, cover systems, and other solid waste management facilities (Schroeder et al., 1994). The primary purpose of the model is to assist in the comparison of design alternatives. The HELP model uses weather, soil and design data to compute a water balance for LF systems accounting for the effects of surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage, and leakage through soil, geomembrane or composite liners. The HELP model can simulate LF systems consisting of various combinations of vegetation, cover soils, waste cells, lateral drain layers, low permeability barrier soils, and synthetic geomembrane liners.

For the IWEM Tier 1 and Tier 2 evaluations, HELP Versions 3.03 and 3.07 were used. We started with an existing database of no-liner infiltration for LFs, WPs and LAUs, and recharge rates for 97 climate stations in the lower 48 contiguous states (ABB, 1995), representing 25 climatic regions, that was developed with HELP version 3.03. To develop the Tier 1 and Tier 2 evaluations, we added five climate stations (located in Alaska, Hawaii, and Puerto Rico) to ensure coverage throughout all of the United States. Figure 4.7 shows the locations of the 102 climate stations.

The current version of HELP (version 3.07) was used for the additional modeling for the no-liner scenario. We compared the results of Version 3.07 against Version 3.03 and found that the differences in calculated infiltration rates were insignificant. We also used this comparison to verify a number of counter-intuitive infiltration rates that were generated with HELP Version 3.03. We had observed that for some climate stations located in areas of the country with low precipitation rates, the net infiltration for unlined LFs did not always correlate with the relative permeability of the LF cover. We found some cases in which a less permeable cover resulted in a higher modeled infiltration rate as compared to a more permeable cover. Examples can be seen in the detailed listing of infiltration data in Appendix D. Table D-1 shows that for a number of climate stations, including Albuquerque, Denver, and Las Vegas, the modeled infiltration rate for LFs with a silty clay loam (SCL) cover is higher than the values corresponding to silt loam (SLT) and sandy loam (SNL) soil covers. We determined that in all these cases, the HELP modeling results for unlined LFs were correct and could be explained in terms of other water balance components, including surface run-off and evapotranspiration.

Table 4.2 Methodology Used to Compute Infiltration for LFs

	No Liner	Single Liner	Composite Liner
Method	HELP model simulations to compute an empirical distribution of infiltration rates for a 2 ft. thick cover of three native soil cover types using nationwide coverage of climate stations. Soil-type specific infiltration rates for a specific site are assigned by using the infiltration rates for respective soil types at the nearest climate station.	HELP model simulations to compute an empirical distribution of infiltration rates through a single clay liner using nationwide coverage of climate stations. Infiltration rates for a specific site were obtained by using the infiltration rate for the nearest climate station.	Compiled from literature sources (TetraTech, 2001) for composite liners
Final Cover	Monte Carlo selection from distribution of soil cover types. 2 ft thick native soil (1 of 3 soil types: silty clay loam, silt loam, and sandy loam) with a range of mean hydraulic conductivities (4.2×10^{-5} cm/s to 7.2×10^{-4} cm/s).	3 ft thick clay cover with a hydraulic conductivity of 1×10^{-7} cm/sec and a 10 ft thick waste layer. On top of the cover, a 1 ft layer of loam to support vegetation and drainage and a 1 ft percolation layer.	No cover modeled; the composite liner is the limiting factor in determining infiltration
Liner Design	No liner	3 ft thick clay liner with a hydraulic conductivity of 1×10^{-7} cm/sec. No leachate collection system. Assumes constant infiltration rate (assumes no increase in hydraulic conductivity of liner) over modeling period.	60 mil HDPE layer with either an underlying geosynthetic clay liner with maximum hydraulic conductivity of 5×10^{-9} cm/sec, or a 3-foot compacted clay liner with maximum hydraulic conductivity of 1×10^{-7} cm/sec. Assumes same infiltration rate (i.e., no increase in hydraulic conductivity of liner) over modeling period.
IWEM Infiltration Rate	Monte Carlo selection from HELP generated location-specific values.	Monte Carlo selection from HELP generated location-specific values.	Monte Carlo selection from distribution of leak detection system flow rates.

Table 4.3 Methodology Used to Compute Infiltration for SIs

	No Liner	Single Liner	Composite Liner
Method	EPACMTP SI module for infiltration through consolidated sludge and native soil layers with a unit-specific ponding depth from EPA's SI Study (EPA, 2001).	EPACMTP module for infiltration through a layer of consolidated sludge and a single clay liner with unit-specific ponding depth from EPA's SI study.	Bonaparte equation (1989) for pin-hole leaks using distribution of leak densities for units installed with formal CQA programs
Ponding Depth	Unit-specific based on EPA's SI study.	Unit-specific based on EPA's SI study.	Unit-specific based on EPA's SI study.
Liner Design	None. However, barrier to infiltration is provided by layer of consolidated sludge at the bottom of the impoundment, and a layer of clogged native soil below the consolidated sludge. The sludge thickness is assumed to be constant over the modeling period. The hydraulic conductivity of the consolidated sludge is between 1.3×10^{-7} and 1.8×10^{-7} cm/sec. The hydraulic conductivity of the clogged native material is assumed to be 0.1 of the unaffected native material in the vadose zone.	3 ft thick clay liner with a hydraulic conductivity of 1×10^{-7} cm/sec. No leachate collection system. Assumes no increase in hydraulic conductivity of liner over modeling period. Additional barrier is provided by a layer of consolidated sludge at the bottom of the impoundment, see no-liner column.	60 mil HDPE layer with either an underlying geosynthetic clay liner with maximum hydraulic conductivity of 5×10^{-9} cm/sec, or a 3-foot compacted clay liner with maximum hydraulic conductivity of 1×10^{-7} cm/sec. Assumptions: 1) constant infiltration rate (i.e., no increase in hydraulic conductivity of liner) over modeling period; 2) geomembrane liner is limiting factor that determines infiltration rate.
IWEM Infiltration Rate	Calculated by EPACMTP based on Monte Carlo selection of unit-specific ponding depth.	Calculated based on Monte Carlo selection of unit-specific ponding depth	Calculated based on Monte Carlo selection of unit-specific ponding depth and distribution of leak densities

Table 4.4 Methodology Used to Compute Infiltration for WPs

	No Liner	Single Liner	Composite Liner
Method	HELP model simulations to compute distribution of infiltration rates for a 10 ft. thick layer of waste, using three waste permeabilities (copper slag, coal bottom ash, coal fly ash) and nationwide coverage of climate stations. Waste-type-specific infiltration rates for a specific site are obtained by using the infiltration rates for respective waste types at the nearest climate station.	HELP model simulations to compute distribution of infiltration rates through 10 ft. waste layer using three waste permeabilities and nationwide coverage of climate stations. Infiltration rates for a specific site were obtained by using the infiltration rate for the nearest climate station.	Compiled from literature sources (TetraTech, 2001) for composite liners
Cover	None	None	None
Liner Design	No liner.	3 ft thick clay liner with a hydraulic conductivity of 1×10^{-7} cm/sec, no leachate collection system, and a 10 ft thick waste layer. Assumes no increase in hydraulic conductivity of liner over unit's operational life.	60 mil HDPE layer with either an underlying geosynthetic clay liner with maximum hydraulic conductivity of 5×10^{-9} cm/sec, or a 3-foot compacted clay liner with maximum hydraulic conductivity of 1×10^{-7} cm/sec. 1) same infiltration rate (i.e., no increase in hydraulic conductivity of liner) over unit's operational life; 2) geomembrane is limiting factor in determining infiltration rate.
IWEM Infiltration Rate	Monte Carlo selection from HELP generated location-specific values.	Monte Carlo selection from HELP generated location-specific values.	Monte Carlo selection from distribution of leak detection system flow rates

Table 4.5 Methodology Used to Compute Infiltration for LAUs

	No Liner	Single Liner	Composite Liner
Method	HELP model simulations to compute an empirical distribution of infiltration rates for a 0.5 ft thick sludge layer, underlain by a 3 ft layer of three types of native soil using nationwide coverage of climate stations. Soil-type specific infiltration rates for a specific site are assigned by using the infiltration rates for respective soil types at the nearest climate station.	N/A	N/A
Liner Design	No liner	N/A	N/A
IWEM Infiltration Rate	Monte Carlo selection from HELP generated location specific values.	N/A	N/A

Figure 4.7 Locations of HELP Climate Stations

The first 97 climate stations were grouped into 25 climate regions based on ranges of average annual precipitation and pan evaporation, as shown in Table 4.6. For each modeled climate station, HELP provides a database of five years of climatic data. We used this climatic data, along with data on the regional soil type and WMU design characteristics, to calculate a water balance for each applicable liner design as a function of the amount of precipitation that reaches the top surface of the unit, minus the amount of runoff and evapotranspiration. The HELP model then computed the net amount of water that infiltrates through the surface, waste, and liner layers, based on the initial moisture content and the hydraulic conductivity of each layer.

In addition to climate factors and liner designs, the infiltration rates calculated by HELP are affected by LF cover design, permeability of the waste material in WP, and LAU soil type. For every climate station and WMU type, we calculated three HELP infiltration rates. In Tier 1, for a selected WMU type and liner design, we used the EPACMTP Monte Carlo modeling process to select randomly from among the HELP-derived infiltration and recharge data, to capture both the nationwide variation in climate conditions, as well as variations in LF soil cover type and WP waste permeability. In Tier 2, the WMU location is a required user input, and the climate factors used in HELP are therefore also fixed; however, Tier 2 still accounts for local variability in LF soil cover type and WP waste permeability.

The factors related to soil type that affect the HELP-generated infiltration and recharge rates are the permeability of the soil used in the LF cover, and – in the case of recharge or for LAU units – the permeability of the soil type in the vicinity of the WMU. We used a consistent set of soil properties in the infiltration and recharge rate calculations as we did in the unsaturated zone fate and transport simulations (see Section 4.2.3). We used HELP to calculate infiltration and recharge for sandy loam, silty loam, and silty clay loam soils.

In the case of WPs, which do not have a cover, the permeability of the waste material itself plays a role similar to that of a LF cover in regulating infiltration rate. We modeled WPs with three different waste types, having different waste permeabilities, and each having equal likelihood of occurrence. The data for the different waste types are presented in Section 4.2.2.2.

Table 4.6 Grouping of Climate Stations by Average Annual Precipitation and Pan Evaporation (ABB, 1995)

City	State	Climate Region		City	State	Climate Region	
		Precipitation (in/yr)	Evaporation (in/yr)			Precipitation (in/yr)	Evaporation (in/yr)
Boise	ID	< 16	< 30	Columbia	MO	32 - 40	30 - 40
Fresno	CA			Put-in-Bay	OH		
				Madison	WI		
Bismarck	ND	< 16	30 - 40	Columbus	OH		
Denver	CO			Cleveland	OH		
Grand Junction	CO			Des Moines	IA		
Pocatello	ID			E. St. Louis	IL		
Glasgow	MT						
Pullman	WA			Topeka	KS	32 - 40	40 - 50
Yakima	WA						
Cheyenne	WY			Tampa	FL	32 - 40	50 - 60
Lander	WY			San Antonio	TX		
Rapid City	SD	< 16	40 - 50	Portland	ME	40 - 48	< 30
Los Angeles	CA			Hartford	CT		
Sacramento	CA			Syracuse	NY		
San Diego	CA			Worchester	MA		
Santa Maria	CA			Augusta	ME		
Ely	NV			Providence	RI		
Cedar City	UT			Nashua	NH		
				Ithaca	NY		
Albuquerque	NM	< 16	50 - 60	Boston	MA		
				Schenectady	NY		
Las Vegas	NV	< 16	> 60				
Phoenix	AZ			NY City	NY	40 - 48	30 - 40
Tucson	AZ			Lynchburg	VA		
El Paso	TX			Philadelphia	PA		
				Seabrook	NJ		
Medford	OR	16 - 24	30 - 40	Indianapolis	IN		
Great Falls	MT			Cincinnati	OH		
Salt Lake City	UT			Bridgeport	CT		

Table 4.6 Grouping of Climate Stations by Average Annual Precipitation and Pan Evaporation (ABB, 1995) (continued)

City	State	Climate Region: Precipitation (in/yr)	Climate Region: Evaporation (in/yr)	City	State	Climate Region: Precipitation (in/yr)	Climate Region: Evaporation (in/yr)
Grand Island	NE	16 - 24	40 - 50	Jacksonville	FL	40 - 48	40 - 50
				Orlando	FL		
Flagstaff	AZ	16 - 24	50 - 60	Greensboro	NC		
				Watkinsville	GA		
Dodge City	KS	16 - 24	> 60	Norfolk	VA		
Midland	TX			Shreveport	LA		
St. Cloud	MN	24 - 32	< 30	Astoria	OR	> 48	< 30
				New Haven	CT		
E. Lansing	MI	24 - 32	30 - 40	Plainfield	MA		
North Omaha	NE	24 - 32	40 - 50	Nashville	TN	> 48	30 - 40
				Knoxville	TN		
Dallas	TX	24 - 32	50 - 60	Central Park	NY		
Tulsa	OK			Lexington	KY		
Brownsville	TX			Edison	NJ		
Oklahoma City	OK	24 - 32	>60	Atlanta	GA	> 48	40 - 50
				Little Rock	AK		
Bangor	ME	32 - 40	< 30	Tallahassee	FL		
Concord	NH			New Orleans	LA		
Pittsburgh	PA			Charleston	SC		
Portland	OR			W. Palm Beach	FL		
Caribou	ME						
Chicago	IL			Lake Charles	LA	> 48	50 - 60
Burlington	VT			Miami	FL		
Rutland	VT						
Seattle	WA						
Montpelier	VT						
Sault St. Marie	MI						

4.2.2.2 Infiltration Rates for Unlined Units

Landfill

We used the HELP model to simulate infiltration through closed LFs for each of the 102 climate station locations shown in Figure 4.7. A 2-foot cover was included as the minimum Subtitle D requirement. Three different soil cover types were modeled: sandy loam, silty loam, and silty clay loam soils. Table 4.7 presents the hydraulic parameters for these three soil types.

Table 4.7 Hydraulic Parameters for the Modeled Soils

Soil Type	HELP Soil Number	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)
Sandy Loam	6	0.453	0.190	0.085	0.000720
Silt Loam	9	0.501	0.284	0.135	0.000190
Silty Clay Loam	12	0.471	0.342	0.210	0.000042

Other LF design criteria included:

- A cover crop of "fair" grass — this is the quality of grass cover suggested by the HELP model for LFs where limitations to root zone penetration and poor irrigation techniques may limit grass quality.

- The evaporation zone thickness selected for each location was generally the depth suggested by the model for that location for a fair grass crop; however, the evaporation zone thickness was not allowed to exceed the soil thickness (24 inches).

- The leaf area index (LAI) selected for each location was that of fair grass (2.0) unless the model indicated a lower maximum for that location.

- The LF configuration was based on a one-acre facility with a 2% top slope and a drainage length of 200 feet (one side of a square acre). Runoff was assumed to be possible from 100% of the cover.

Appendix D, Table D-1, presents the infiltration rate data for the 102 climate stations. The unlined LF infiltration rate for each soil type at each of the 102 climate centers was used as the ambient regional recharge rate for that climatic center and soil type.

Surface Impoundment

We calculated SI infiltration rates using the built-in SI module in EPACMTP (see Section 3.1). This means that for EPACMTP, the SI infiltration rate is not really an input parameter, rather the model calculates infiltration rates "on the fly" during the simulation, as a function of impoundment ponding depth and other SI characteristics. For unlined SIs, the primary parameters that control the infiltration rate are the ponding depth in the impoundment, the thickness and permeability of any accumulated sediment layer at the base of the impoundment, and the presence of a 'clogged' (i.e., reduced permeability) layer of native soil underneath the impoundment caused by the migration of solids from the impoundment. In addition, IWEM checks that the calculated infiltration rate does not result in an unrealistic degree of ground-water mounding (see Section 4.2.6).

For IWEM, we used unit-specific data on SI ponding depths from EPA's *Surface Impoundment Study* (U.S. EPA, 2001). We assumed a fixed sediment layer thickness of 20 cm at the base of the impoundment. The resulting sediment layer permeability has a relatively narrow range of variation between 1.26×10^{-7} and 1.77×10^{-7} cm/s. We assumed that the depth of clogging underneath the impoundment was 0.5 m in all cases, and that saturated hydraulic conductivity of the clogged layer is 10% of that of the native soil underlying the impoundment. The parameters used to calculate SI infiltration rates are tabulated as part of the Tier 1 parameter tables in Appendix C.

In the event that the SI is reported to have its base below the water table, we calculated the infiltration using Darcy's law based on the hydraulic gradient across and the hydraulic conductivity of the consolidated sediment at the bottom of the impoundment unit.

Waste Pile

For the purpose of estimating leaching rates, we considered WPs to be similar to non-covered LFs with a total waste thickness of 10 feet. The infiltration rates for unlined WPs were, therefore, generated with the HELP model using the same general procedures as for LFs, but with the following modifications:

- *No cover*
  We modeled the leachate flux through active, uncovered piles. We modeled the WP surface as having no vegetation. The evaporative zone depth was taken as the suggested HELP model value for the "bare"

condition at each climate center. The LAI was set to zero to eliminate transpiration.

- *Variable waste permeability*
  For uncovered WPs, we found that the infiltration rates predicted by HELP model are sensitive to the permeability of the waste material itself. Based on these results, we simulated WP infiltration rates for three different WP materials: relatively high permeability, moderate permeability, and relatively low permeability. Parameters for the three waste types are presented in Table 4.8.

Table 4.8 Moisture Retention Parameters for the Modeled WP Materials

Waste Type	HELP Soil Number	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)
Low Permeability	30	0.541	0.187	0.047	0.00005
Moderate Permeability	31	0.578	0.076	0.025	0.00410
High Permeability	33	0.375	0.055	0.020	0.04100

We calculated WP infiltration rates for all 102 climate stations and waste material permeabilities. Appendix D, Table D-2, presents the WP infiltration rate values for all climate stations and waste types.

Land Application Unit

LAUs were modeled with HELP using two soil layers. The top layer was taken as six inches in thickness and represented the layer into which the waste was applied. The bottom layer was of the same material type as the top layer and was set at a thickness of 36 inches. Both of these layers were modeled as vertical percolation layers. The same three soil types for LFs were also used for LAUs.

We assumed the waste applied to the LAU to be a sludge-type material with a high water content. We also assumed a waste application rate of 7.25 inches per year (in/yr) with the waste having a solids content of 20% and a unit weight of 75 lb/ft^3. Assuming that 100% of the water in the waste was available as free water, an excess water amount of 5.8 in/yr, in addition to precipitation, would be available for percolation. HELP model analyses showed that the additional water available for percolation generally would have little effect on the simulated water balance and net infiltration, except for sites located in arid regions of the United States with very little natural precipitation. For more representative waste application rates, the effect disappeared because introducing additional moisture in the simulated water balance results in a commensurate increase in runoff and removal by evapotranspiration. The LAU infiltration values are presented in Appendix D, Table D-3.

4.2.2.3 Single-Lined Waste Units

IWEM includes infiltration rates for lined LFs, WPs, and SIs. In the case of LAUs, only unlined units are considered.

Landfill

We calculated infiltration rates for single-lined LFs using the HELP model. We modeled the LF as a four-layer system, consisting, from top to bottom of:

- 1-foot percolation cover layer;
- 3-foot compacted clay cover with hydraulic conductivity of 1×10^{-7} cm/s ;
- 10-foot thick waste layer; and
- 3-foot thick compacted clay liner with a hydraulic conductivity of 1×10^{-7} cm/sec.

We simulated the cover layer as a loam drainage layer supporting a “fair” cover crop with an evaporative zone depth equal to that associated with a fair cover crop at the climate center. The remaining conditions were identical to those described in Section 4.2.2.2 for unlined LFs.

In developing infiltration rates for Tier 1, we used the grouping of climate stations into 25 regions of similar climatic conditions depicted in Table 4.6 in order to reduce the number of required HELP simulations. Rather than calculating infiltration rates for each of the 102 individual climate stations, we calculated infiltration rates for the 25 climate regions, and then assigned the same value to each climate station in one group. To ensure a protective result, we chose the climate center with the highest average precipitation in each climate region as representative of that region. Appendix D, Table D-4, shows the infiltration rate values for clay-lined LFs that we used in developing the Tier 1 LCTVs. The actual climate stations that were used in the HELP simulations for each climate region are shown in bold face in the table. We calculated individual infiltration rates for the five climate centers in Alaska, Hawaii, and Puerto Rico that were not assigned to a climate region.

We used the database of HELP-generated infiltration rates to provide estimates of LF infiltration rates in Tier 2 when a user does not have site-specific data. During the process of assembling the HELP infiltration values for the IWEM software tool, we realized that the grouping of climate centers into regions for clay-lined units, resulted in a number of apparent anomalies in which the suggested infiltration rate for a lined unit would be higher than the unlined infiltration rate at the same climate station. This resulted from the fact that we used the infiltration rate for the climate center with the highest annual precipitation in each region for clay-lined units, but then compared it with a location-specific infiltration value for unlined units. The occurrence of these anomalies was restricted to climate stations in arid parts of the United States, and was noticeable only when the absolute magnitude of infiltration was low. In order to remove these counter-intuitive results, we re-calculated location-specific HELP infiltration rates for clay-lined units at 17 climate stations (Glasgow, MT; Yakima, WA; Lander, WY; Cheyenne, WY; Pullman, WA; Pocatello, ID; Grand Junction, CO; Denver, CO; Great Falls, MT; Salt Lake City, UT; Cedar City, UT; El Paso, TX; Ely, NV; Las Vegas, NV; Rapid City, SD; Phoenix, AZ; and Tucson, AZ). We then incorporated location-specific infiltration rates for these 17 climate stations into the Tier 2 IWEM software, to replace the regional values used for these stations in Tier 1.

As a result of the additional HELP model simulations for clay-lined units that we performed after the Tier 1 LCTVs had been generated, the database of infiltration rates that is incorporate into the IWEM software is slightly different from the data used in Tier 1. We performed a sensitivity analysis to assess what would have been the impact on Tier 1 LCTVs had we used location-specific infiltration values, rather than regional values, for the 17 climate stations involved. We used three constituents in the sensitivity analysis: a weakly sorbing constituent (benzene, K_{oc} = 63 mL/g); a moderately sorbing constituent (carbon tetrachloride, K_{oc} = 257 mL/g); and a strongly sorbing constituent (heptachlor, K_{oc} = 162,000 mL/g). Table 4.9 summarizes the results of this sensitivity analysis. This table follows the format of the Tier 1 LCTV tables presented in Appendix F of this report.

For each of the three constituents, Table 4.9 compares the actual Tier 1 LCTVs to values calculated using location-specific infiltration rates for the 17 climate stations. The updated values are shaded and shown in bold-face. The table indicates that if we had used these data in the Tier 1 evaluations, it would have resulted in slightly higher LCTVs for some constituents, notably weakly to moderately sorbing constituents. Constituents that are strongly sorbing (as represented by heptachlor), and/or that rapidly degrade, would be less affected because the LCTVs for these constituents are often controlled by various imposed caps (see Section 6). Even for the constituents that are affected, the change in LCTV would have been very slight. The largest LCTV impact in Table 4.9 is 0.004 mg/L for the MCL-based LCTV of carbon tetrachloride. The sensitivity analysis shows that the use of regional infiltration rates for clay-lined LFs in Tier 1 resulted in slightly more protective LCTVs than if we had used location-specific values. This confirms the intent of Tier 1 to provide protective screening values.

Table 4.9 Sensitivity Analysis of Tier 1 LCTVs for Clay-lined LFs to Regional Versus Location-specific Infiltration Rates for 17 Climate Stations

Constituent	LCTV based on MCL (mg/L)	Non-Carc. Effect		Carc. Effect	
		LCTV based on Ingestion	LCTV based on Inhalation	LCTV based on Ingestion	LCTV based on Inhalation
Benzene TIER 1	0.030		0.50 [a]	0.011	0.010
Benzene REVISED INFIL.DATA	**0.033**		**0.50 [a]**	**0.012**	**0.010**
Carbon tetrachloride TIER 1	0.055	0.2	0.23	8.2E-03	8.4E-03
Carbon tetrachloride REVISED INFIL.DATA	**0.059**	**0.2**	**0.25**	**8.7E-03**	**8.9E-03**
Heptachlor TIER 1	8.0E-03 [a]	8.0E-03 [a]		8.0E-03 [a]	8.0E-03 [a]
Heptachlor REVISED INFIL.DATA	**8.0E-03 [a]**	**8.0E-03 [a]**		**8.0E-03 [a]**	**8.0E-03 [a]**

[a] TC Rule exit level cap

Waste Pile

We calculated infiltration rates for single-lined WPs using the HELP model. We modeled the WP as a two-layer system, consisting, from top to bottom, of:

- 10-foot thick, uncovered, waste layer; and
- 3-foot thick compacted clay liner with a hydraulic conductivity of 1×10^{-7} cm/sec.

Other parameters were set to the same values as in the unlined WP case. The same three waste material types were used as in Tier 1. We also modeled a bare surface for the evaporative zone depth.

In developing WP infiltration rates for Tier 1, we used the same grouping of climate stations in 25 climate regions as previously discussed for LFs. Appendix D, Table D-4, shows the infiltration rate values for clay-lined WPs that we used in developing the Tier 1 LCTVs. The actual climate centers that were used in the HELP simulations for each climate region are shown in bold face in the table. We calculated individual infiltration rates for the five climate centers in Alaska, Hawaii, and Puerto Rico that were not assigned to a climate region.

Analogous to the situation encountered for LFs, we found a number of apparent anomalies between WP infiltration rates for unlined as compared to clay-lined WPs, resulting from the use of regional infiltration values for clay-lined units. The occurrence of these anomalies for WPs was also restricted to climate centers in arid parts of the United States, for which the absolute magnitude of infiltration was low. In order to remove these counter-intuitive results, we re-calculated location-specific HELP infiltration rates for clay-lined WP units at 17 climate stations (Glasgow, MT; Yakima, WA; Lander, WY; Cheyenne, WY; Pullman, WA; Pocatello, ID; Grand Junction, CO; Denver, CO; Great Falls, MT; Salt Lake City, UT; Cedar City, UT; El Paso, TX; Ely, NV; Las Vegas, NV; Rapid City, SD; Phoenix, AZ; and Tucson, AZ). We then incorporated location-specific infiltration rates for these 17 climate stations into the Tier 2 IWEM software to replace the regional values used for these stations in Tier 1.

We also assessed the impact on Tier 1 LCTVs had we used location-specific infiltration values, rather than regional values, for the 17 climate stations. Table 4.10 summarizes the results of this sensitivity analysis for WP units. This table follows the format of the Tier 1 LCTV tables presented in Appendix F of this report. For each of the three constituents, the table compares the actual Tier 1 LCTVs to values calculated using location-specific infiltration rates for the 17 climate stations given above. The updated values are shaded and shown in bold-face. The results of the sensitivity analysis for WPs are consistent with, and of similar magnitude, as the results we found for LFs.

Table 4.10 indicates that if we had used the additional location-specific infiltration data in the Tier 1 evaluations, it would have resulted in slightly higher LCTVs for some constituents, notably weakly to moderately sorbing constituents. Constituents that are strongly sorbing (as represented by heptachlor), and/or that rapidly degrade, would be less affected because the LCTVs for these constituents are often controlled by various imposed caps (see Section 6). Even for the constituents that are affected, the change in LCTV would have been very slight. The largest LCTV impact in Table 4.10 is 0.03 mg/L for the MCL-based LCTV of carbon tetrachloride. The sensitivity analysis shows that the use of regional infiltration rates for clay-lined WPs in Tier 1 resulted in slightly more protective LCTVs than if we had used location-specific values. This confirms the intent of Tier 1 to provide protective screening values.

During the process of verifying the HELP-generated infiltration rates for clay-lined units we also replaced incorrect values for clay-lined WPs assigned to the Lake Charles, LA and Miami, FL climate stations. These two climate stations have high precipitation (Table 4.6), but were assigned low infiltration rates in the Tier 1 analyses (see Appendix D, Table D-4). We re-ran the HELP model for the clay-lined WP scenario for the three clay-lined WP scenarios, that is low, medium, and high waste permeability.

Table 4.10 Sensitivity Analysis of Tier 1 LCTVs for Clay-lined WPs to Regional Versus Location-specific Infiltration Rates for 17 Climate Stations

Constituent	LCTV based on MCL (mg/L)	Non-Carc. Effect		Carc. Effect	
		LCTV based on Ingestion	LCTV based on Inhalation	LCTV based on Ingestion	LCTV based on Inhalation
Benzene TIER 1	0.13		0.50 [a]	0.06	0.056
Benzene REVISED INFIL.DATA	**0.15**		**0.50 [a]**	**0.07**	**0.064**
Carbon tetrachloride TIER 1	0.21	0.50 [a]	0.50 [a]	0.043	0.044
Carbon tetrachloride REVISED INFIL.DATA	**0.24**	0.50 [a]	0.50 [a]	**0.048**	**0.049**
Heptachlor TIER 1	8.0E-03 [a]	8.0E-03 [a]		8.0E-03 [a]	8.0E-03 [a]
Heptachlor REVISED INFIL.DATA	**8.0E-03 [a]**	**8.0E-03 [a]**		**8.0E-03 [a]**	**8.0E-03 [a]**

[a] TC Rule exit level cap

The re-calculated infiltration rate values averaged 0.066 m/yr, as compared to 0.019 m/yr in Tier 1. We incorporated the re-calculated values in the IWEM software tool for Tier 2. Note that the underestimation of infiltration rates for Lake Charles and Miami will have had the effect of partially compensating for overestimating infiltration rates at other locations in the national Tier 1 screening analysis.

Surface Impoundment

For single-lined SIs, infiltration rates were calculated inside of EPACMTP in the same manner as described in the previous section for unlined units, with the exception that we added a 3-foot compacted clay liner with a hydraulic conductivity of 1×10^{-7} cm/s at the bottom of the WMU and we did not include the effect of clogged native material due to the filtering effects of the liner.

4.2.2.4 Infiltration Rates for Composite-Lined Units

We conducted an information collection effort that involved searching the available literature for data that quantify liner integrity and leachate infiltration through composite liners (TetraTech, 2001). We assembled these data and applied them to develop the Tier 1 and Tier 2 analyses as follows:

Landfill and Waste Pile

We treated composite-lined LFs and WPs as being the same for the purpose of determining infiltration rates. For these WMU's, we developed an infiltration rate distribution from actual leak detection system (LDS) flow rates reported for clay composite-lined LF cells.

We based the distribution of composite-lined LF and WP infiltration rates on available monthly average LDS flow rates from 27 LF cells reported by TetraTech (2001). The data and additional detail for the 27 LF cells are provided in Appendix D, Table D-5. The data included monthly average LDS flow rates for 22 operating LF cells and 5 closed LF cells. The 27 LF cells are located in eastern United States: 23 in the northeastern region, 1 in the mid-Atlantic region, and 3 in the southeastern region. Each of the LF cells is underlain by a geomembrane/ geosynthetic clay liner which consists of a geomembrane of thickness between 1 and 1.5 mm (with the majority, 22 of 27, being 1.5 mm thick), overlying a geosynthetic clay layer of reported thickness of 6 mm. The geomembrane is a flexible membrane layer made from HDPE. The geosynthetic clay liner is a composite barrier consisting of two geotextile outer layers with a uniform core of bentonite clay to form a hydraulic barrier. The liner system is underlain by a LDS.

We decided in this case to use a subset of the reported flow rates compiled by TetraTech (2001) in developing the composite liner infiltration rates for IWEM. We did not include LDS flow rates for geomembrane/compacted clay composite-lined LF cells in our distribution. For compacted clay liners (including composite geomembrane/ compacted clay liners), there is the potential for water to be released during the consolidation of the clay liner and yield an unknown contribution of water to LDS flow, such that it is very difficult to determine how much of the LDS flow is due to liner leakage, versus how much is due to clay consolidation. We also decided in this case to not use LDS flow rates from three geomembrane/geosynthetic clay lined-cells. For one cell, flow rate data were available for the cell's operating period and the cell's post-closure period. The average flow rate for the cell was 26 liters/hectare/day when the cell was operating and 59 liters/hectare/day when the cell was closed. We believe these flow rates, which were among the highest reported, are difficult to interpret because the flow rate from the closed cell was over twice the flow rate from the open cell, a pattern inconsistent with the other open cell/closed cell data pairs we reviewed. For the two other cells, additional verification of the data may be needed in order to fully understand the reported flow rates.

The resulting cumulative probability distribution of infiltration rates for composite-lined LFs and WPs for use in this application is based on the 27 remaining data points is presented in Table 4.11. Note that over 50% of the values are zero, that is, they have no measurable infiltration.

Table 4.11 Cumulative Frequency Distribution of Infiltration Rate for Composite-Lined LFs and WPs

Percentile	**0**	**10**	**25**	**50**	**75**	**90**	**100**
Infiltration Rate (m/yr)	0.0	0.0	0.0	0.0	7.30×10^{-5}	1.78×10^{-4}	4.01×10^{-4}

Surface Impoundment

We calculated leakage through circular defects (pin holes) in a composite liner using the following equation developed by Bonaparte et al. (1989):

$$Q = 0.21 a^{0.1} h^{0.9} K_s^{0.74}$$

where:

- Q = steady-state rate of leakage through a single hole in the liner (m^3/s)
- a = area of hole in the geomembrane (m^2)
- h = head of liquid on top of geomembrane (m)
- K_s = hydraulic conductivity of the low-permeability soil underlying the geomembrane (m/s)

This equation is applicable to cases where there is good contact between the geomembrane and the underlying compacted clay liner. For each SI unit, we determined its infiltration rate using the above equation. We used the unit-specific ponding depth data (corresponding to h in the above equation) from the recent *Surface Impoundment Study* (U.S. EPA, 2001) in combination with a distribution of leak densities (expressed as number of leaks per hectare) compiled from 26 leak density values reported in TetraTech (2001). The leak densities are based on liners installed with formal Construction Quality Assurance (CQA) programs.

The 26 sites with leak density data are mostly located outside the United States: 3 in Canada, 7 in France, 14 in United Kingdom, and 2 with unknown locations. The WMUs at these sites (8 LFs, 4 SIs, and 14 unknown) are underlain by a layer of geomembrane of thickness varying from 1.14 to 3 mm. The majority of the geomembranes are made from HDPE (23 of 26) with the remaining 3 made from prefabricated bituminous geomembrane or polypropylene. One of the sites has a layer of compacted clay liner beneath the geomembrane, however, for the majority of the sites (25 of 26) material types below the geomembrane layer are not reported. The leak density data above were used for SIs. The leak density distribution is shown in Table 4.12. Table D-6, Appendix D, provides additional detail.

To use the Bonaparte equation, we assumed a uniform leak size of 6 millimeters squared (mm^2). The leak size is the middle of a range of hole sizes reported by Rollin et al. (1999), who found that 25 percent of holes were less than 2 mm^2, 50 percent of holes were 2 to 10 mm^2, and 25 percent of holes were greater than 10 mm^2. We assumed that the geomembrane is underlain by a compacted clay liner whose hydraulic conductivity is 1×10^{-7} cm/s.

In order to ascertain the plausibility of the leak density data, we conducted an infiltration rate calculation to estimate the range of infiltration resulting from the leaks in geomembrane. Because of the absence of documented infiltration data for SIs, we used the infiltration data for LFs, described previously under the LF and WP section, as a surrogate infiltration data set for comparison purposes. Because the comparison was made on the basis of LF data, we set the head of liquid above the geomembrane to 0.3 m (1 foot) which is a typical maximum design head for LFs. Calculation results are shown in Table D-6, Appendix D. The results indicate that the calculated leakage rates, based on the assumptions of above-geomembrane head, hole dimension, hydraulic conductivity of the barrier underneath the geomembrane, and good contact between the geomembrane and the barrier, agree favorably with the observed LF flow rates reported in Table D-5, Appendix D. This result provided confidence that the leak density data could be used as a reasonable basis for calculating infiltration rates using actual SI ponding depths.

The resulting frequency distribution of calculated infiltration rates for composite-lined SIs used in Tier 1 is presented in Table 4.13. For Tier 2, the user is required to specify the unit's ponding depth. IWEM will then determine the unit's infiltration distribution using the Bonaparte equation and the leak density distribution in Table 4.12.

Table 4.12 Cumulative Frequency Distribution of Leak Density for Composite-Lined SIs

Percentile	0	10	20	30	40	50	60	70	80	90	100
Leak density (No. Leaks/ha)	0	0	0	0	0.7	0.915	1.36	2.65	4.02	4.77	12.5

Table 4.13 Cumulative Frequency Distribution of Infiltration Rate for Composite-Lined SIs

Percentile	0	10	25	50	75	90	100
Infiltration Rate (m/yr)	0.0	0.0	0.0	1.34×10^{-5}	1.34×10^{-4}	3.08×10^{-4}	4.01×10^{-3}

4.2.2.5 Determination of Recharge Rates

We estimated recharge rates for the three primary soil types across the United States (SNL, SLT, and SCL) and ambient climate conditions at 102 climate stations through the use of the HELP water-balance model as summarized in 4.2.2.1. We assumed the ambient regional recharge rate for a given climate center and soil type (for all four WMU types) is the same as the corresponding unlined LF infiltration rate.

4.2.3 Parameters Used to Describe the Unsaturated and Saturated Zones

We used a number of data sources to obtain parameter values for the unsaturated and saturated zone modeling in Tier 1 and Tier 2. A primary data source was the Hydrogeologic Database for Ground-Water Modeling (HGDB), assembled by Rice University on behalf of the American Petroleum Institute (API) (Newell et al, 1989). This database provides probability distributions of a number of key ground-water modeling parameters for various types of subsurface environments.

For unsaturated zone modeling, we used a database of soil hydraulic properties for various soil types, assembled by Carsel and Parrish (1988), in combination with information from the Soil Conservation Service (SCS) on the nationwide prevalence of different soil types across the United States.

4.2.3.1 Subsurface Parameters

The HGDB database provides site-specific data on four key subsurface parameters[6]:

- Depth to ground water;
- Saturated zone thickness;
- Saturated zone hydraulic conductivity; and
- Saturated zone hydraulic gradient;

The data in this hydrogeological database were collected by independent investigators for approximately 400 hazardous waste sites throughout the United States. In the HGDB, the data are grouped into twelve subsurface environments, which are based on EPA's DRASTIC classification of hydrogeologic settings (U.S. EPA, 1985). Table 4.14 lists the subsurface environments. The table includes a total of 13 categories; 12 are distinct subsurface environments, while the 13th category, which is labeled "other" or

[6] The database also provides data on ground-water seepage velocity and on "vertical penetration depth" of a waste plume below the water table. We did not use these data. EPACMTP calculates the ground-water velocity directly and the vertical penetration depth is not used in EPACMTP.

"unknown", was used for waste sites that could not be classified into one of the first 12 environments. The subsurface parameter values in this 13th category are simply averages of the parameter values in the 12 actual subsurface environments. Details on the individual parameter distributions for each subsurface environment are provided in the *EPACMTP Parameters/Data Background Document* (U.S. EPA, 2002b).

Table 4.14 HGDB Subsurface Environments (from Newell et al, 1989)

Region	Description
1	Metamorphic and Igneous
2	Bedded Sedimentary Rock
3	Till Over Sedimentary Rock
4	Sand and Gravel
5	Alluvial Basins Valleys and Fans
6	River Valleys and Floodplains with Overbank Deposit
7	River Valleys and Floodplains without Overbank Deposits
8	Outwash
9	Till and Till Over Outwash
10	Unconsolidated and Semi-consolidated Shallow Aquifers
11	Coastal Beaches
12	Solution Limestone
13	Other (Not classifiable)

The key feature of this database is that it provides a set of correlated values of the four parameters for each of the 400 sites in the database. That is, the value of each parameter is associated with the three other subsurface parameters reported for the same site. We preserved these correlations because having information on some parameters allows us to develop more accurate estimates for missing parameter values.

In Tier 1 we used the HGDB in conjunction with a geographical classification of aquifers developed by the United States Geological Survey (Heath, 1984) to assign each waste site in our nationwide database of Subtitle D WMU's (see Section 4.2.1) to one of the 13 subsurface environments. For each type of WMU, we used information on its location (see Figures 4.2 - 4.5), in combination with USGS state-by-state aquifer maps to determine the type of subsurface environment at that site. Sites that could not be classified into one of the 12 categories were assigned as "other" (that is, they were assigned to environment number 13). Using the subsurface parameters in the HGDB for each of the 13 environments, we could then assign a probability distribution of parameter values to each WMU location. This methodology is consistent with how we assigned HELP-derived infiltration and recharge rates to each WMU in the IWEM modeling database.

In Tier 2, the type of subsurface environment, as well as each of the four individual subsurface parameters (depth to ground water, saturated thickness, saturated hydraulic conductivity, and hydraulic gradient) are optional, site-specific user inputs. Depending on the extent of available site data, IWEM will use statistical correlations developed from the HGDB to estimate missing or unknown parameters. If site-specific values for all four parameters are known, then Tier 2 will use these values and in this case, information on the type of subsurface environment is not needed. If one or more of the four subsurface parameters are unknown, but the type of subsurface environment at the site is known, Tier 2 will use the known parameters to generate a probability distribution for the unknown parameters, using the statistical correlations that correspond to the type of environment at the site. If no site-specific hydrogeologic information is known, IWEM will treat the site as being in subsurface environment number 13 and assign values that are national averages.

4.2.3.2 Unsaturated Zone Parameters

To model flow of infiltration water through the unsaturated zone, we used data on unsaturated hydraulic properties assembled by Carsel and Parrish (1988) in conjunction with information from the SCS on the nationwide prevalence of different soil types across the United States. First, we used SCS soil mapping data to estimate the relative prevalence of light- (sandy loam), medium- (silt loam), and heavy-textured (silty clay loam) soils across the United States. The estimated percentages are shown in Table 4.15. The soil types used in the unsaturated zone modeling were also used in the HELP model to derive infiltration and recharge rates (See Section 4.2.2) in order to have a consistent set of soil modeling parameters. We then used the soil property data reported by Carsel and Parrish to determine the probability distributions of individual soil parameters for each soil type, and used these distributions in the Monte Carlo modeling for Tier 1 and Tier 2. Table 4.16 presents the unsaturated zone parameter values used in the Tier 1 and Tier 2 development.

Table 4.15 Nationwide Distribution of Soil Types Represented in IWEM

Texture Category	SCS Soil Type	Relative Frequency (%)
Light textured	Sandy Loam	15.4
Medium textured	Silt Loam	56.6
Heavy textured	Silty Clay Loam	28.0

Table 4.16 Statistical Parameters for Soil Properties for Three Soil Types Used in IWEM Tier 1 and Tier 2 Development (Carsel and Parrish, 1988)

Parameter[1]	Distribution Type[2]	Limits of Variation		Mean	Standard Deviation
		Minimum	Maximum		
Soil Type - Silty Clay Loam					
K_{sat} (cm/hr)	SB	0	3.5	0.017	2.921
θ_r	NO	0	0.115	0.089	0.0094
α (cm$^{-1)}$	SB	0	0.15	.009	.097
β	NO	1.0	1.5	1.236	0.061
% OM	SB	0	8.35	0.11	5.91
ρ_b	Constant	-	-	1.67	-
θ_s	Constant	-	-	0.43	-
Soil Type - Silt Loam					
K_{sat} (cm/hr)	LN	0	15.0	.343	.989
θ_r	SB	0	0.11	.068	0.071
α (cm$^{-1)}$	LN	0	0.15	.019	0.012
β	SB	1.0	2.0	1.409	1.629
% OM	SB	0	8.51	0.105	5.88
ρ_b	Constant	-	-	1.65	-
θ_s	Constant	-	-	0.45	-
Soil Type - Sandy Loam					
K_{sat} (cm/hr)	SB	0	30.0	2.296	24.65
θ_r	SB	0	0.11	0.065	0.074
α (cm^{-1})	SB	0	0.25	0.070	0.171
β	LN	1.35	3.00	1.891	0.155
% OM	SB	0	11.0	0.074	7.86
ρ_b	Constant	-	-	1.60	-
θ_s	Constant	-	-	0.41	-

[1] K_{sat} is saturated hydraulic conductivity; θ_r is residual water content; α, β are retention curve parameters; % OM is percent Organic Matter, ρ_b is bulk density; θ_s is saturated water content.

[2] NO is Normal (Gaussian) distribution; SB is Log ratio distribution where $Y = \ln[(x-A)/(B-x)]$, $A < x < B$; LN is Log normal distribution, $Y = \ln[x]$, where Y = normal distributed parameter

The parameters α, β, and θ_r in Table 4.16 are specific to the Mualem-Van Genuchten model that is employed in the EPACMTP unsaturated zone flow module described in Section 3.2 (see the *EPACMTP Technical Background Document* for details).

In addition to the soil hydraulic parameters listed in Table 4.16, IWEM also requires certain soil transport parameters. These are the soil bulk density and percent organic matter, which are used to calculate the constituent-specific retardation coefficients, the unsaturated zone dispersivity, and the soil pH and temperature. The latter two parameters are used to calculate hydrolysis transformation rates; pH is also a key parameter for modeling transport of metals. Soil bulk density and percent organic matter were obtained from the Carsel and Parrish (1988) database and are presented in Table 4.16. These parameters are used to calculate the retardation factor in the constituent transport equation (Section 3.2). We used the data on the percent organic matter to calculate the fraction organic carbon according to:

$$foc = \frac{\%\ OM}{174}$$

where:

foc	=	Mass fraction organic carbon in the soil (kg/kg)
% *OM*	=	Percent organic matter
174	=	Conversion constant

We calculated dispersivity in the unsaturated zone, α_{uz} as a function of the travel distance (D_u, m) between the base of the WMU and the water table, according to the following relationship:

$$\alpha_{uz} = 0.02 + (0.022 \times D_u)$$

where:

α_{uz}	=	longitudinal dispersivity in the unsaturated zone (m)
D_u	=	Depth of the unsaturated zone, from the base of the WMU to the water table (m)

This relationship is based on a regression analysis of field scale transport data presented by Gelhar et al. (1985). We capped the maximum allowed value of dispersivity at one meter in IWEM.

Soil temperature and pH were obtained from nationwide distributions. For these parameters we used the same distributions for the entire aquifer, that is, both for the unsaturated zone and for the saturated zone. In both the Tier 1 and Tier 2 evaluations, we used a nationwide aquifer pH distribution, derived from EPA's STORET database. The pH distribution is an empirical distribution with a median value of 6.8 and lower and upper bounds of 3.2 and 9.7, respectively, as shown in Table 4.17.

Table 4.17 Probability Distribution of Soil and Aquifer pH

Percentile	0	1	5	10	25	50	75	90	95	99	100
pH Value	3.20	3.60	4.50	5.20	6.07	6.80	7.40	7.90	8.2	8.95	9.7

As modeled in IWEM, soil and aquifer temperature affects the transformation rate of constituents that are subject to hydrolysis, through the effect of temperature on reaction rates (see Section 4.2.4.1). In the IWEM development, we used information on average annual temperatures in shallow ground-water systems (Todd, 1980) to assign a temperature value to each WMU in the modeling database, based on the unit's geographical location. For each WMU site, the assigned temperature was an average of the upper and lower values for that temperature region, as shown in Figure 4.8. In other words, all WMU's located in the band between 10° and 15° were assigned a temperature value of 12.5 degrees C.

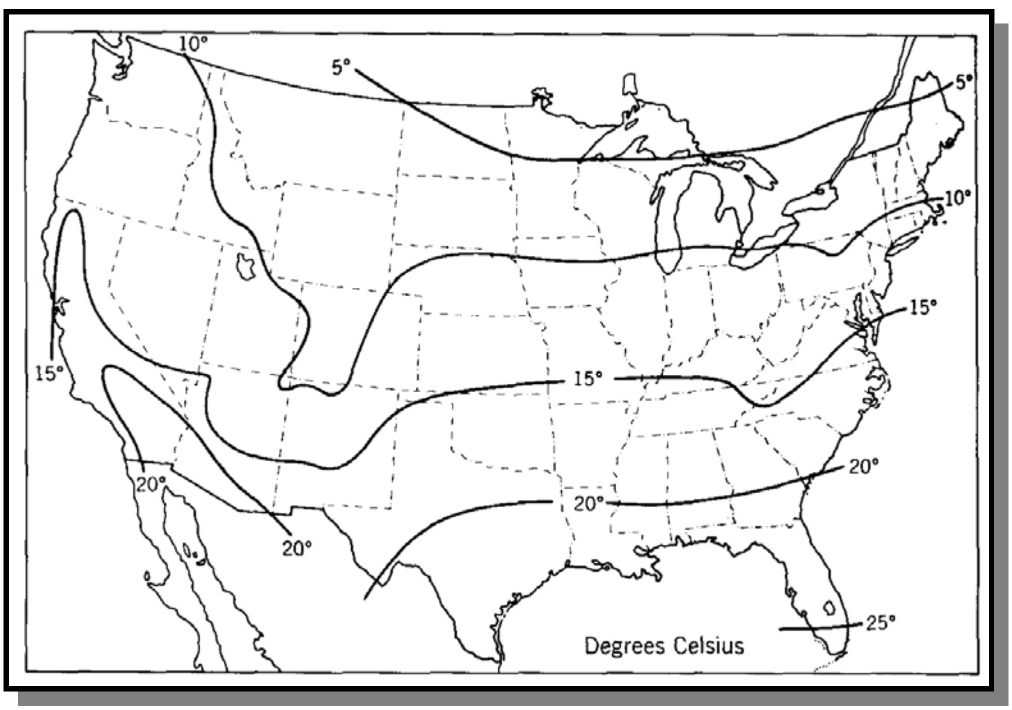

Figure 4.8 Ground-water Temperature Distribution for Shallow Aquifers in the United States (from Todd, 1980).

IWEM Monte Carlo Methodology for Soil Parameters

In both Tier 1 and Tier 2, we assumed that soil properties are uniform at each site. That is, while we selected a new set of soil parameters for each realization in the Tier 1 and Tier 2 modeling process, the soil properties were assumed uniform for a given realization. However, the methodology for assigning soil types differed. In Tier 1, we randomly selected one of the three soil types shown in Table 4.15 for each realization, with a probability given by each soil type's frequency of occurrence, i.e., we would select silt loam soils in 56.6% of the realizations, sandy loam soils in 15.4% of the cases, and silty clay loam soils in 28% of the cases. The selection of the soil type also determines the distribution of recharge and – for unlined and single-lined LF, WP, and LAUs – the infiltration rate through the unit (see Section 4.2.2). Based on the selected soil type, values for each of the unsaturated zone modeling parameters were generated using the distributions presented in Table 4.16.

In Tier 2, the soil type is a optional site-specific user input parameter. Because the site location must always be entered by the user, the selection of the soil type determines the recharge rate, as well as the HELP-derived infiltration rates which the IWEM tool will use in the evaluation. Based on the selected soil type, the IWEM tool will randomly select values for the parameters in Table 4.16 from the probability distributions corresponding to the soil type. If the soil type in Tier 2 is entered as "unknown", the Tier 2 Monte Carlo process for the unsaturated zone parameters will default to that used in Tier 1, that is, IWEM will randomly select one of the three possible soil types in accordance with their nationwide frequency of occurrence.

4.2.3.3 Saturated Zone Parameters

In addition to the four site-related subsurface parameters discussed in Section 4.2.3.1, IWEM requires a number of additional saturated zone transport parameters. They are: saturated zone porosity; saturated zone bulk density; longitudinal, transverse and vertical dispersivities; fraction organic carbon; aquifer temperature; and aquifer pH.

Saturated zone porosity is used in the calculation of the ground-water seepage velocity; saturated zone porosity and bulk density are used in the calculation of constituent-specific retardation coefficients. In IWEM, we used default, nationwide distributions for aquifer porosity and bulk density, that is, they are not user inputs. Both were derived from a distribution of aquifer particle diameter presented by Shea (1974). This distribution is presented in Table 4.18. Using the data in Table 4.18 as an input distribution, IWEM calculates porosity, ϕ, from particle diameter using an empirical relationship based on data reported by Davis (1969) as:

$$\phi = 0.261 - 0.0385 \, ln \, (d)$$

where

ϕ = Porosity (dimensionless)
d = Mean particle diameter (cm)
ln = Natural logarithm

Additionally, we used relationships presented in McWorther and Sunada (1977), to establish relationships between total (ϕ) and effective porosity (ϕ_e) as a function of mean particle diameter, see Table 4.19.

Table 4.18 Empirical Distribution of Mean Aquifer Particle Diameter (from Shea, 1974)

Percentile	0.0	3.8	10.4	17.1	26.2	37.1	56.0	79.2	90.4	94.4	97.6	100
Particle Diameter (cm)	3.9×10^{-4}	7.8×10^{-4}	0.0016	0.0031	0.0063	0.0125	0.025	0.05	0.1	0.2	0.4	0.8

Table 4.19 Ratio Between Effective and Total Porosity as a Function of Particle Diameter (after McWorther and Sunada, 1977)

Mean Particle Diameter (cm)	ϕ_e/ϕ Range
$\leq 6.25\times10^{-3}$	0.03 - 0.77
6.25×10^{-3} - 2.5×10^{-2}	0.04 - 0.87
2.5×10^{-2} - 5.0×10^{-2}	0.31 - 0.91
5.0×10^{-2} - 10^{-1}	0.58 - 0.94
$> 10^{-1}$	0.52 - 0.95

IWEM calculates apparent saturated zone dispersivities as a function of the distance between the waste unit and the modeled ground-water well, using regression relationships based on a compilation of field-scale dispersivity data in Gelhar et al. (1985). These relationships are:

$$\alpha_L(x) = \alpha_L^{REF} \times (x/152.4)^{0.5}$$
$$\alpha_T = \alpha_L/8$$
$$\alpha_V = \alpha_L/160$$

where

x	=	downgradient ground-water travel distance (m)
α_L	=	longitudinal dispersivity (m)
α_T	=	horizontal transverse dispersivity (m)
α_V	=	vertical transverse dispersivity (m)
α_L^{REF}	=	reference dispersivity value (m)

We used the longitudinal dispersivity corresponding to a distance of 152.4 m (500 feet) as a reference to calculate dispersivity at different well distances, according to the probability distribution presented in Table 4.20.

Table 4.20 Cumulative Probability Distribution of Longitudinal Dispersivity at Reference Distance of 152.4 m (500 ft)

Percentile	0.0	1.00	70.0	100.0
Dispersivity, $\alpha_L^{REF}(m)$	0.1	1.0	10.0	100.0

We used data as the fraction organic carbon in the aquifer (f_{oc}) to model sorption of organic constituents, as discussed in Section 3.2. In the development of the IWEM Tier 1 and Tier 2 evaluations, we used a nationwide distribution obtained from values of dissolved organic carbon in EPA's STORET water quality database. The distribution was modeled as a Johnson SB frequency distribution (see *EPACMTP Parameters/Data Background Document*) with a mean of 4.32×10^{-4}, a standard deviation of 0.0456, and lower and upper limits of 0.0 and 0.064, respectively.

We determined values of the ground-water temperature and pH in the same manner as we did for soil pH and temperature (see Section 4.2.3.2).

4.2.4 Parameters Used to Characterize the Chemical Fate of Constituents

For the Tier 1 and Tier 2 evaluations the chemical fate of constituents as they are transported through the subsurface is presented in terms of an overall first-order decay coefficient, a retardation coefficient which reflects equilibrium sorption reactions, and for transformation daughter-products, a production term that represents the formation of daughter compounds due to the transformation of parent constituents.

This section describes how we developed constituent-specific parameter values for these chemical fate processes. Section 4.2.4.1 describes constituent transformation processes, while Section 4.2.4.2 discusses all constituent degradation processes. Section 4.2.4.3 describes how we modeled sorption processes. Section 4.2.4.4 describes the criteria we applied to determine whether constituents could be treated as being effectively non-reactive (i.e., zero transformation and sorption) in developing the Tier 1 evaluation.

4.2.4.1 Constituent Transformation

For organic constituents, IWEM accounts for chemical and biological transformations by considering a first-order overall degradation coefficient in the transport analysis (see Section 3.2). In Tier 1, we considered only hydrolysis reactions. In Tier 2, the default hydrolysis rate coefficients in the IWEM constituent database can be replaced with a user-specified overall degradation rate that can account for any type of transformation process, including biodegradation.

Hydrolysis

Hydrolysis refers to the transformation of chemical constituents through reactions with water. For organic constituents, hydrolysis can be one of the main degradation processes that occur in soil and ground water and is represented in the EPACMTP model by means of an overall first-order chemical decay coefficient. For modeling hydrolysis in the Tier 1 and Tier 2 evaluations, we used constituent-specific hydrolysis rate constants compiled at the EPA's Environmental Research Laboratory in Athens, GA (Kollig et al., 1993). These are listed in Appendix B.

The hydrolysis process as modeled in IWEM is affected by both aquifer pH, aquifer temperature and constituent sorption, through the following equations. The tendency of each constituent to hydrolyze is expressed through constituent-specific acid-catalyzed $(K_a^{T_r})$, neutral $(K_n^{T_r})$ and base-catalyzed $(K_b^{T_r})$ rate constants. The superscript T_r indicates that the values are measured at a specified reference temperature, T_r. First, the values of the rate constants are modified to account for the effect of aquifer temperature through the Arrhenius equation:

$$K_J^T = K_J^{T_r} \; exp \; [E_a/R_g(\frac{1}{T_r + 273} - \frac{1}{T + 273})]$$

where:

K_J^T	=	Hydrolysis rate constant for reaction process J and temperature T
J	=	*a* for acid, *b* for base, and *n* for neutral
T	=	Temperature of the subsurface (°C)
T_r	=	Reference temperature (°C)
R_g	=	Universal gas constant (1.987E-3 Kcal/deg-mole)
E_a	=	Arrhenius activation energy (Kcal/mole)

Next, the effect of pH on hydrolysis rates is incorporated via:

$$\lambda_1 = K_a^T [H^+] + K_n^T + K_b^T [OH^-]$$

where

λ_1	=	First-order decay rate for dissolved phase (1/yr)
K_a^T, K_n^T, K_b^T	=	Hydrolysis rate constants
$[H^+]$	=	Hydrogen ion concentration (mole/L)
$[OH^-]$	=	Hydroxyl ion concentration (mole/L)

$[H^+]$ and $[OH^-]$ are computed from the pH of the soil or aquifer using

$[H^+]$ = 10^{-pH}

$[OH^-]$ = $10^{-(14-pH)}$

The sorbed phase hydrolysis rate is calculated as:

$$\lambda_2 = 10 K_a^T [H^+] + K_n^T$$

where:

λ_2	=	First-order hydrolysis rate for sorbed phase (1/yr)
K_a^T	=	Acid-catalyzed hydrolysis rate constant (1/mole/yr)
K_n^T	=	Neutral hydrolysis rate constant (1/yr)
10	=	Acid-catalyzed hydrolysis enhancement factor

Finally, the overall first-order transformation rate for hydrolysis is calculated as:

$$\lambda = \frac{\lambda_1 \phi + \lambda_2 \rho_b k_d}{\phi + \rho_b k_d}$$

where:

λ	=	Overall first-order hydrolysis transformation rate (1/yr)
λ_1	=	Dissolved phase hydrolysis transformation rate (1/yr)
λ_2	=	Sorbed phase hydrolysis transformation rate (1/yr)
ϕ	=	Porosity (water content in the unsaturated zone) (dimensionless)
ρ_b	=	Bulk density (kg/L)
k_d	=	Partition coefficient (L/kg)

We used the information on hydrolysis transformation pathways presented in Kollig et al. (1993) to identify toxic hydrolysis daughter products; Section 6 of this document describe how we incorporated this information into the determination of Tier 1 and Tier 2 LCTVs.

4.2.4.2 Other Constituent Degradation Processes

Many organic constituents may be subject to biodegradation in the subsurface, and in Tier 2, the IWEM tool allows the user to provide a constituent-specific overall degradation coefficient, which can include both aerobic or anaerobic biodegradation. IWEM does not specifically simulate biodegradation reactions, and therefore, the IWEM user must ensure that the value entered is representative of actual site conditions, and that the transformation reactions can be adequately characterized as a first-order rate process, (that, is a process that can be represented in terms of a characteristic half-life). The overall degradation rate parameter that is used as a Tier 2 input is related to the constituent's subsurface half-life and is expressed as:

$$\lambda = 0.693/t_{1/2}$$

where

λ	=	IWEM degradation rate input value (1/yr)
$t_{½}$	=	Constituent half-life (yr)

4.2.4.3 Constituent Sorption

In addition to physical and biological transformation processes, the transport of constituents can be affected by a wide range of complex geochemical reactions. From a practical view, the important aspect of these reactions is the removal of solute from solution, irrespective of the process. For this reason IWEM lumps the cumulative effects of the geochemical processes into a single term (i.e., solid-water partition coefficient) which is one of several parameters needed to describe the degree to which a constituents mobility is retarded relative to ground water. In the EPACMTP fate and transport model upon which IWEM is based, this process is defined by the retardation factor defined in Section 3.2. The remainder of this section describes the procedures we used to model sorption for organic constituents and inorganic constituents, specifically, metals.

4.2.4.3.1 Sorption Modeling for Organic Constituents

For organic constituents we determined k_d values as the product of the constituent-specific K_{oc} and the fraction organic carbon in the soil or ground water:

$$k_d = K_{oc} \times f_{oc}$$

where

k_d	=	partition coefficient (L/kg),
K_{oc}	=	normalized organic carbon distribution coefficient (kg/L), and
f_{oc}	=	fractional organic carbon content (dimensionless)

K_{oc} values for IWEM constituents are listed in Appendix B. For IWEM, we calculated the fraction organic carbon in the unsaturated zone from the percent organic matter in the soil (see section 4.2.3.2) as:

$$f_{oc} = \frac{\%OM}{174}$$

where

f_{oc}	=	fractional organic carbon content (kg/kg),
$\%OM$	=	percent organic matter in the soil, and
174	=	conversion factor.

In the saturated zone modeling we used the nation-wide data on the fraction organic carbon on ground water to provide direct values for f_{oc} (see Section 4.2.3.3)

4.2.4.3.2 Sorption Modeling for Inorganic Constituents (Metals)

Partition coefficients (k_d) for metals in the IWEM tool modeling are selected from non-linear sorption isotherms estimated using the geochemical speciation model, MINTEQA2. For a particular metal, k_d values in a soil or aquifer are dependent upon the metal concentration and various geochemical characteristics of the soil or aquifer and the associated porewater.

Geochemical parameters that have the greatest influence on the magnitude of k_d include the pH of the system and the nature and concentration of sorbents associated with the soil or aquifer matrix. In the subsurface beneath a disposal facility, the concentration of leachate constituents may also influence k_d. Although the dependence of metal partitioning on the total metal concentration and on pH and other geochemical characteristics is apparent from partitioning studies reported in the scientific literature, the reported k_d values for individual metals do not cover the range of metal concentrations or geochemical conditions relevant in the IWEM scenarios. For this reason, we chose to use an equilibrium speciation model, MINTEQA2, to estimate metals partition coefficients for the IWEM development. We used the speciation model to estimate k_d values for a range of total metal concentrations in various model systems designed to depict natural variability in those geochemical characteristics that most influence metal partitioning.

From input data consisting of total concentrations of inorganic chemicals, MINTEQA2 calculates the fraction of a constituent metal that is dissolved, adsorbed, and precipitated at equilibrium. The ratio of the adsorbed fraction to the dissolved fraction is the dimensionless partition coefficient. We converted the dimensionless partition coefficient to k_d with units of liters per kilogram (L/kg) by normalizing the mass of soil (in kg) with one liter of porewater in which it is equilibrated (the phase ratio).

We used MINTEQA2 to develop isotherms for Antimony (Sb-5+), Arsenic (As-3+ and As-5+) Barium (Ba), Beryllium (Be), Cadmium (Cd), Chromium (Cr-3+ and Cr-6+), Cobalt (Co), Copper (Cu), Fluoride (F), Manganese (Mn-2+), Mercury (Hg), Lead (Pb), Molybdenum (Mo-5+), Nickel (Ni), Selenium (Se-4+ and Se-6+), Silver (Ag), Thallium (Tl-1+), Vanadium (V-5+), and Zinc (Zn).

MINTEQA2 Input Parameters

We accounted for the expected natural variability in k_d for a particular metal in the MINTEQA2 modeling by including variability in important input parameters upon which k_d depends. The input parameters for which variability was incorporated include ground-water compositional type, pH, concentration of sorbents, and concentration of metal. In addition, we varied the concentration of representative anthropogenic organic acids that may be present in leachate from a waste site.

We modeled two ground-water compositional types – one with composition representative of a carbonate-terrain system and one representative of a non-carbonate system. The two ground-water compositional types are correlated with the subsurface environment (see Section 4.2.3.1, Table 4.14). The carbonate type corresponds to the "solution limestone" subsurface environment setting. The other eleven subsurface environments in IWEM are represented by the non-carbonate ground-water type. If the subsurface environment is “unknown”, then IWEM will also assume it is a non-carbonate type. For both ground-water types, a representative, charge-balanced ground-water chemistry specified in terms of major ion concentrations and natural pH was selected from the literature. The carbonate system was represented by a sample reported in a limestone aquifer. This ground water had a natural pH of 7.5 and was saturated with respect to calcite. The non-carbonate system was represented by a sample reported from an unconsolidated sand and gravel aquifer with a natural pH of 7.4. We selected an unconsolidated sand and gravel aquifer to represent the non-carbonate compositional type because it is the most frequently occurring of the twelve subsurface environments in HGDB database.

We included two types of adsorbents in modeling the k_d values: ferric oxide (FeOx) and particulate organic matter (POM). Mineralogically, the ferric oxide was assumed to be goethite (FeOOH). We used a database of sorption reactions for goethite reported by Mathur (1995) with the diffuse-layer sorption model in MINTEQA2 to represent the interactions of protons and metals with the goethite surface. The concentration of sorption sites used in the model runs was based on a measurement of ferric iron extractable from soil samples using hydroxylamine hydrochloride as reported in EPRI (1986). This method of Fe extraction is intended to provide a measure of the exposed amorphous hydrous oxide of Fe present as mineral coatings and discrete particles and available for surface reaction with pore water. The variability in FeOx content represented by the variability in extractable Fe from these samples was included in the modeling by selecting low, medium and high FeOx concentrations corresponding to the 17^{th} , 50^{th} and 83^{rd} percentiles of the sample measurements. The specific surface area and site density used in the diffuse-layer model were as prescribed by Mathur. Although we used the same distribution of extractable ferric oxide sorbent in the saturated and unsaturated zones, the actual concentration of sorbing sites corresponding to the low, medium, and high FeOx settings in MINTEQA2 was different in the two zones because the phase ratio was different (4.57 kg/L in the unsaturated zone; 3.56 kg/L in the saturated zone.)

We obtained the concentration of the second adsorbent, POM, from organic matter distributions already present in the IWEM modeling database. In the unsaturated zone, low, medium, and high concentrations for components representing POM in the MINTEQA2 model runs were based on the distribution of solid organic matter for the silt loam soil type. (The silt loam soil type is intermediate in weight percent organic matter in comparison with the sandy loam and silty clay loam soil types and is also the most frequently occurring soil type among the three.) The low, medium, and high POM concentrations used in the saturated zone MINTEQA2 model runs were obtained from the organic matter distribution for the saturated zone. For both the FeOx and POM adsorbents, the amount of sorbent included in the MINTEQA2 modeling was scaled to correspond with the phase ratio in the unsaturated and saturated zones.

We obtained a dissolved organic matter (DOM) distribution for the saturated zone from the EPA's STORET database. This distribution was used to provide low, medium, and high DOM concentrations for the MINTEQA2 model runs. The low, medium, and high DOM values were used exclusively with the low, medium, and high values, respectively, of POM. In the unsaturated zone, there was no direct measurement of DOM available. The ratio of POM to DOM for the three concentration levels (low, medium, high) in the unsaturated zone was assumed to be the same as for the saturated zone. In MINTEQA2, the POM and DOM components were modeled using the Gaussian distribution model. This model includes a database of metal-DOM reactions (Susetyo et al., 1991). Metal reactions with POM were assumed to be identical in their mean binding constants with the DOM reactions.

Leachate exiting a WMU may contain elevated concentrations of anthropogenic leachate organic acids (LOA). We included representative carboxylic acids for leachate from industrial WMUs in the MINTEQA2 modeling. An analysis of total organic carbon (TOC) in LF leachate by Gintautas et al. (1993) was used to select and quantify the organic acids. We assigned the low, medium, and high values for the representative acids in the modeling based on the lowest, the average, and the highest measured TOC among the six LF leachates analyzed. Because we expect leachate from industrial WMUs to be lower in organic matter than in municipal LFs, we included only the low and medium LOA values in IWEM.

MINTEQA2 Modeling and Results

We conducted the MINTEQA2 modeling separately for each metal in three steps for the unsaturated zone, and these were repeated for the saturated zone:

- Sorbents were pre-equilibrated with ground waters: Each of nine possible combinations of the two FeOx and POM sorbent concentrations (low FeOx, low POM; low FeOx, medium POM; etc.) were equilibrated with each of the two ground-water types (carbonate and non-carbonate). Because the sorbents adsorb some ground-water constituents (calcium, magnesium, sulfate, fluoride), the input total concentrations of these constituents were adjusted so that their equilibrium dissolved concentrations in the model were equal to their original (reported) ground-water dissolved concentrations. This step was conducted at the natural pH of each ground water, and calcite was imposed as an equilibrium mineral for the carbonate ground-water type. Small additions of inert ions were added to maintain charge balance.

- The pre-equilibrated systems were titrated to new target pH's: Each of the nine pre-equilibrated systems for each ground-water type were titrated with NaOH to raise the pH or with HNO_3 to lower the pH. Nine target pH's spanning the range 4.5 to 8.2 were used for the non-carbonate ground water. Three target pH's spanning the range 7.0 to 8.0 were used for the carbonate ground water. Titration with acid or base to adjust the pH allowed charge balance to be maintained.

- LOAs and the constituent metal were added: Each of the eighty-one pre-equilibrated, pH-adjusted systems of the non-carbonate ground water and the twenty-seven pre-equilibrated, pH-adjusted systems of the carbonate ground water were equilibrated with two concentrations (low and medium) of LOAs. The equilibrium pH was not imposed in MINTEQA2; pH was calculated and reflected the acid and metal additions. The constituent metal was added as a metal salt (e.g., $PbNO_3$) at a series of forty-four total concentrations spanning the range 0.001 mg/L to 10,000 mg/L of metal. Equilibrium composition and K_d were calculated at each of the forty-four total metal concentrations to produce an isotherm of sorbed metal versus metal concentration. The isotherm can also be expressed as k_d versus metal concentration.

This modeling resulted in eighty-one isotherms for the non-carbonate environment and twenty-seven isotherms for the carbonate environment for the unsaturated zone. A like number of isotherms for each environment was produced for the saturated zone. Each isotherm corresponds to a particular setting of FeOx sorbent concentration, POM sorbent (and associated DOM) concentration, leachate acid concentration, and pH. An example isotherm for Cr(VI) is shown in Figure 4.9. This isotherm corresponds to the following conditions: low LOAs, medium FeOX concentration, high POM concentration, for pH 6.3 in unsaturated zone, non-carbonate environment.

We computed isotherms for two environmentally relevant oxidation states of chromium, arsenic, and selenium. The different oxidation states of these metals have different geochemical behavior, and in the case of chromium also distinctly different toxicological behavior. Chromium-3+ exhibits behavior typical of a cation, but chromium-6+ behaves as an anion (chromate). Chromium-3+ and chromate are most strongly sorbed at opposite ends of the pH spectrum: sorption of chromium-3+ tends to increase with pH over the pH range 4 to 8, whereas sorption of chromate tends to decrease with pH over this range. In addition, separate health-based toxicity values have been established for chromium-3+ and chromate. The dissimilarity in sorption behavior and the availability of separate toxicity benchmarks warrants treating chromium-3+ and

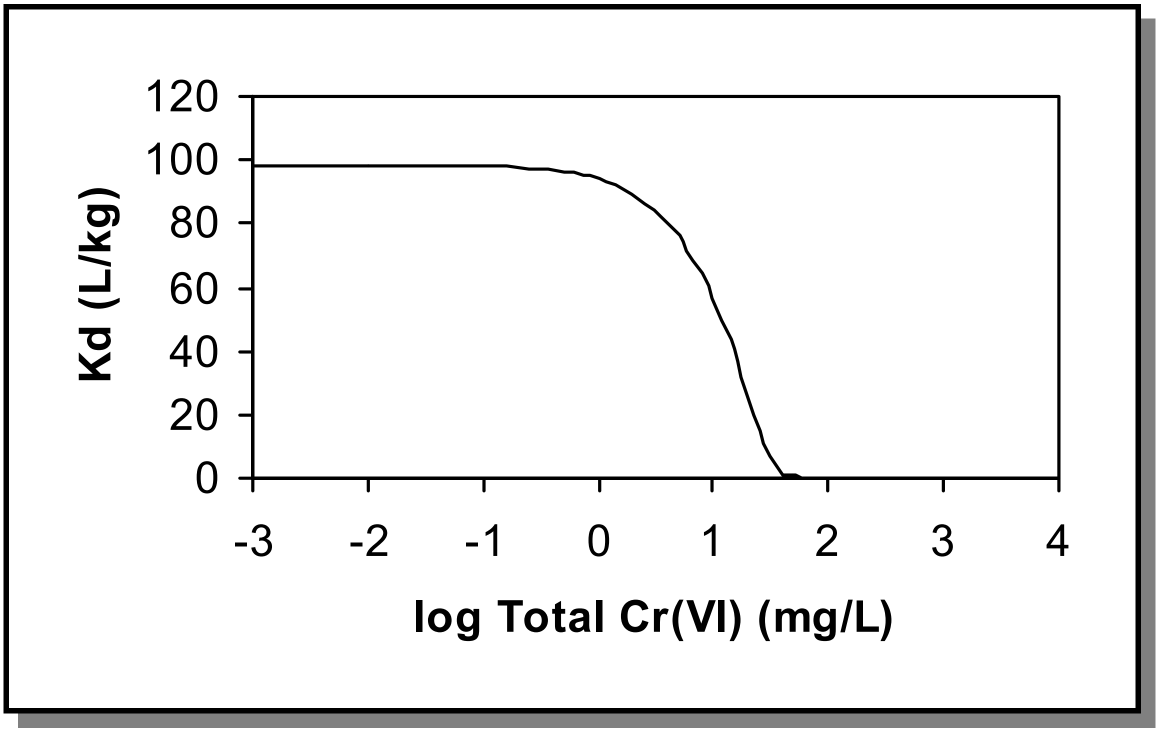

Figure 4.9 Example Unsaturated Zone Isotherm for Cr(VI) Corresponding to Low LOA, Medium FeOx, High POM, pH-6.3.

chromate as if they were separate metals. Thus, IWEM considers chromium-3+ and chromium-6+ as different constituents and we used both sets of Cr isotherms to produce Tier 1 LCTVs for both forms.

The two oxidation states of arsenic and selenium also exhibit differences in sorption behavior, but both metals tend always to behave as anions. Unlike chromium, separate toxicity values have not been established for the two forms of arsenic and selenium. We therefore incorporated the more mobile forms only of arsenic and selenium in IWEM as the more protective approach. We ran EPACMTP with both sets of isotherms for these metals to discover which oxidation state was more mobile. The results indicate that As and Se should be assumed to be present as As-5+ and Se-6+. Accordingly, these are the species used in producing the Tier 1 LCTVs, and partition coefficients for these are provided for use in Tier 2 modeling.

4.2.4.4 Partition Coefficient and Degradation Rate Threshold Criteria EPA Used to Define Conservative Constituents in Developing the Tier 1 Evaluation

In developing the Tier 1 LCTVs, we conducted a very large number of EPACMTP Monte Carlo runs to account for all constituents and combinations of WMU types and liner designs. We expedited these modeling analyses by treating all conservative organic constituents as a single group. This was permissible, because as modeled in EPACMTP, constituents that have the same fate characteristics will show the same subsurface transport behavior.

A conservative chemical is defined as a chemical that neither adsorbs to the soil matrix nor degrades as it is transported through the subsurface. Metals are not regarded as conservative chemicals because they tend to sorb strongly to the soil matrix. Organic chemicals, however, vary in degrees of sorptivity and susceptibility to degradation. Some of the organic chemicals may be approximated as equivalent to conservative chemicals due to their recalcitrance to degradation and low sorptivity. The sorptivity and degradation of organic chemicals are governed by two key parameters: the organic carbon distribution coefficient (K_{oc}) and the effective degradation rate constant (λ), respectively. For an organic to be considered conservative, it must have sufficiently small K_{oc} and λ.

We determined cutoff values for K_{oc} and λ by conducting a sensitivity analysis for selected waste management scenarios, each with several combinations of K_{oc} and λ. Based on the results if this analysis, we used threshold values of K_{oc} = 100 L/kg, and λ = 1×10^{-4} 1/year to categorize constituents as conservative for the purpose of developing the IWEM Tier 1 LCTVs for unlined and single-lined WMUs only. In other words, we treated constituents with K_{oc} and λ values below these thresholds as conservative species. For all composite liner evaluations, we conducted individual Monte Carlo runs for each chemical. The reason is that at the low infiltration rates associated with composite liners, the DAF values predicted by EPACMTP become very sensitive to even small differences in K_{oc} and λ.

4.2.5 Well Location Parameters

In the IWEM Tier 1 and Tier 2 development, we modeled the ground-water exposure location as the intake point of a ground-water well located down gradient from the WMU. The location of the well in IWEM is described by three parameters:

- Downgradient distance from the waste unit (x-location)
- Transverse distance from the plume centerline (y-location)
- Vertical distance below the water table (z-location)

The well location parameters are depicted schematically in Figure 4.10, which shows the location of the well relative to WMU in plan view and in cross-section view.

Downgradient Distance from WMU (m)

This parameter represents the distance between the downgradient edge of the WMU and the position of the well, measured along the direction of ground-water flow. This direction represents the x- coordinate as depicted in Figure 4.10. In Tier 1, we assigned this parameter a fixed value of 150 meters. In Tier 2, this parameter is an optional site-specific user input value, with a maximum allowed value of 1609 meters (1 mile). The default value in Tier 2 is 150 meters.

Well Transverse Distance from the Plume Centerline (m)

This parameter represents the horizontal distance between the well and the modeled centerline of the plume, see Figure 4.10. For the Tier 1 and Tier 2 evaluations, we always set this parameter to zero, that is, we modeled the ground-water well as always being located at the centerline of the plume. This is a protective assumption because the ground-water concentrations predicted by the model will be highest along the centerline of the plume, and decrease with distance away from the centerline.

Well Intake Depth Below the Water Table (m)

This parameter represents the vertical distance of the well intake point below the water table. In calculating the position of the well intake, the model uses the water table elevation before any mounding effects are taken into consideration. In both Tier 1 and Tier 2, we assigned the well depth parameter a uniform probability distribution with a range of 0 - 10 meters. This means that all depth values are between 0 to 10 meters below the water table are equally likely. For each Monte Carlo realization in which the modeled saturated zone thickness is less than 10 meters, the maximum well depth of 10 meters is replaced with the actual saturated zone thickness used in the realization.

4.2.6 Screening Procedures EPA Used to Eliminate Unrealistic Parameter Combinations in the Monte Carlo Process

Inherent to the Monte Carlo process is that parameter values are drawn from multiple data sources, and then combined in each realization of the modeling process. Because the parameter values are drawn randomly from their individual probability distributions, it is possible that parameters are combined in ways that are physically infeasible and that violate the validity of the EPACMTP flow and transport model. We

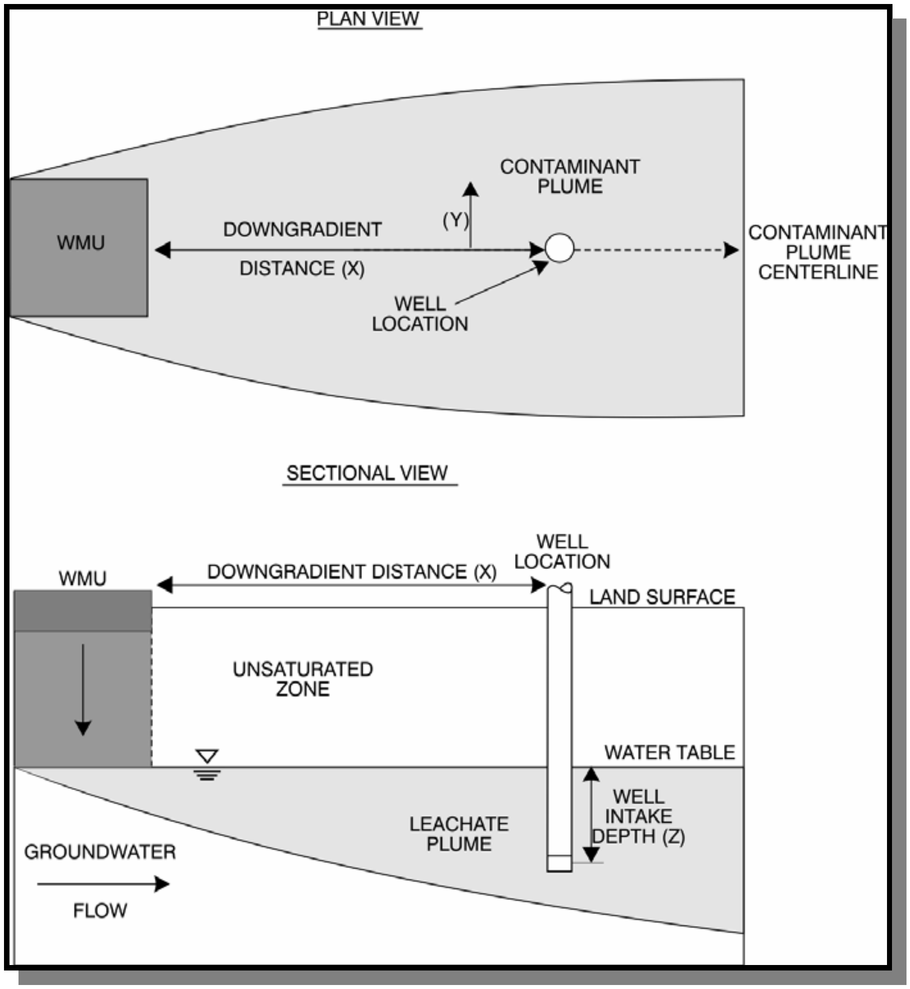

Figure 4.10 Position of the Modeled Ground-water Well Relative to the WMU.

implemented a number of checks to eliminate or reduce these occurrences as much as possible. As a relatively simple measure, upper and lower limits are specified on individual parameter values to ensure that their randomly generated values are within physically realistic limits. Where possible, we used data sources that contained multiple parameters, and implemented these in the Monte Carlo process in a way that preserved the existing correlations among the parameters. For example, we used the HGDB database of subsurface parameters (see Section 4.2.3) in combination with knowledge of the subsurface environments at each waste site location in our WMU parameter database to assign the most appropriate combinations of subsurface parameters to each site.

Likewise, we assigned climate-related parameters based on each site's proximity to an infiltration modeling database of 102 climate stations, as described in Section 4.2.2.

We also specified upper and lower limits on secondary parameters whose values are calculated (derived) internally in the Monte Carlo module as functions of the primary EPACMTP input parameters, see the *EPACMTP Parameters/Data Background Document* (U.S. EPA, 2002b), and implemented a set of screening procedures to ensure that infiltration rates and the resulting predicted ground-water mounding would remain physically plausible. Specifically, we screened the parameter values generated in each Monte Carlo realization for the following conditions:

- Infiltration and recharge so high they cause the water table to rise above the ground surface;

- Water level in a SI unit below the water table, causing flow into the SI; and

- Infiltration rate from a SI exceeds the saturated hydraulic conductivity of the soil underneath.

These screening procedures are discussed in more detail below. Mathematical details of the screening algorithms are presented in the *EPACMTP Technical Background Document* (U.S. EPA, 2002a).

The logic diagram for the infiltration screening procedure is presented in Figure 4.11; Figure 4.12 provides a graphical illustration of the screening criteria. The numbered criteria checks in Figure 4.11 correspond to the numbered diagrams in Figure 4.12. Note that high infiltration rates are most likely with (unlined) SIs. Therefore, the screening procedure is the most involved for SI WMUs.

Figure 4.11(a) depicts the screening procedures for LFS, WPs, and LAUs. For these units, after the four correlated subsurface parameters (depth to water table, aquifer saturated thickness, aquifer hydraulic conductivity, and regional gradient), as well as recharge associated with the selected soil type and the nearest climate center, and source infiltration have been generated for each Monte Carlo realization, the IWEM tool calculates the estimated water table mounding that would result from the selected combination of parameter values. The combination of parameters is accepted if the calculated maximum water table elevation (the ground-water 'mound') remains below the ground surface elevation at the site. If the criterion is not satisfied, the selected parameters for the realization is rejected and a new data set is selected.

For SIs, there are two additional screening steps, as depicted in Figure 4.11(b). At each Monte Carlo realization, a SI unit is selected from the SI WMU database. The unit-specific parameter, including ponding depth, and base depth below ground surface are retrieved from the database. The four correlated subsurface parameters are then selected from the hydrogeologic database, based on the subsurface environment at that WMU location. Using the information on the base depth and water table elevations, we can determine whether the SI unit is hydraulically connected to the water table. If the base of the SI is below the water table, the SI unit is said to be hydraulically connected to the water table (see Figure 4.12, Criterion 1). The realization is rejected and a new set of hydrogeologic parameters is generated if the hydraulically connected SI is an inseeping type, that is, the water surface in the SI is below the water table (see Figure 4.12, Criterion 1(b)). As long as the elevation of the waste water surface in the impoundment is above the watertable, the first criterion is passed (Figure 4.12, Criterion 1(a)).

If the base of the unit is located above the ambient water table, that is, before any adjustment to the water table elevation to account for mounding is made, the unit is said to be hydraulically separated from the water table (see Figure 4.12, Criterion 2). However, in this case, it is necessary to ensure that the calculated infiltration rate does not exceed the maximum feasible infiltration rate. The maximum feasible infiltration rate is the maximum infiltration that allows the water table to be hydraulically separated from the SI. In other words, it is the rate that does not allow the crest of the local ground-water mound to be higher than the base of the SI. This limitation allows us to determine a conservative infiltration rate that is based on the free-drainage condition at the base of the SI. The infiltration rate is no longer conservative if the water table is allowed to be in hydraulic contact with the base of the SI. If the maximum feasible infiltration rate (I_{max}) is exceeded, IWEM will set the infiltration rate to this maximum value.

IWEM handles the screening in this order to accommodate the internal software logic in EPACMTP. If the SI is a hydraulically connected type based on the user-supplied information on the WMU and water table positions, EPACMTP will simulate this system by by-passing the unsaturated zone module. On the other hand, if the hydraulic connection results from water table mounding, i.e., the original water table elevation is below the WMU, EPACMTP cannot easily handle this situation, and the realization is therefore rejected.

Once the infiltration limit has been imposed, the third criterion is checked to ensure that any ground-water mounding does not result in a rise of the water table mound above the ground surface, in the same manner as done for other types of WMU.

In the IWEM software, the parameter constraints are checked after all Tier 2 inputs have been specified, but before the actual EPACMTP Monte Carlo simulations are initiated. The first check applies when the user provides all Tier 2 input parameters as site-specific values. In this case, the software checks that the combination of input values does not violate the infiltration and water table elevation constraints. The second check applies when some Tier 2 inputs are set to site-specific values, while default probability distributions are used for other Tier 2 inputs. In this case, it is possible that the combination of fixed, site-specific values with national or regional distributions, results in a high frequency of rejections in the EPACMTP simulations. An example would be simulating an unlined SI at a site where the depth to ground-water is set to a very small value. This combination is likely to lead to a large number of rejections in the EPACMTP Monte Carlo simulation due to violation of the ground-water mounding constraint. This, in turn, may result in very long EPACMTP run times. It also indicates that IWEM may not be appropriate for that site.

IWEM therefore checks the Tier 2 user inputs through a probabilistic screening routine which generates random combinations of EPACMTP parameter values in accordance with the specified Tier 2 inputs and measures the number of rejections. This routine will check that 20,000 acceptable parameter combinations can be generated in 100,000 or less random realizations. If the inputs fail this test, the software will report the most frequently violated constraint and suggest potential remedies in the user inputs.

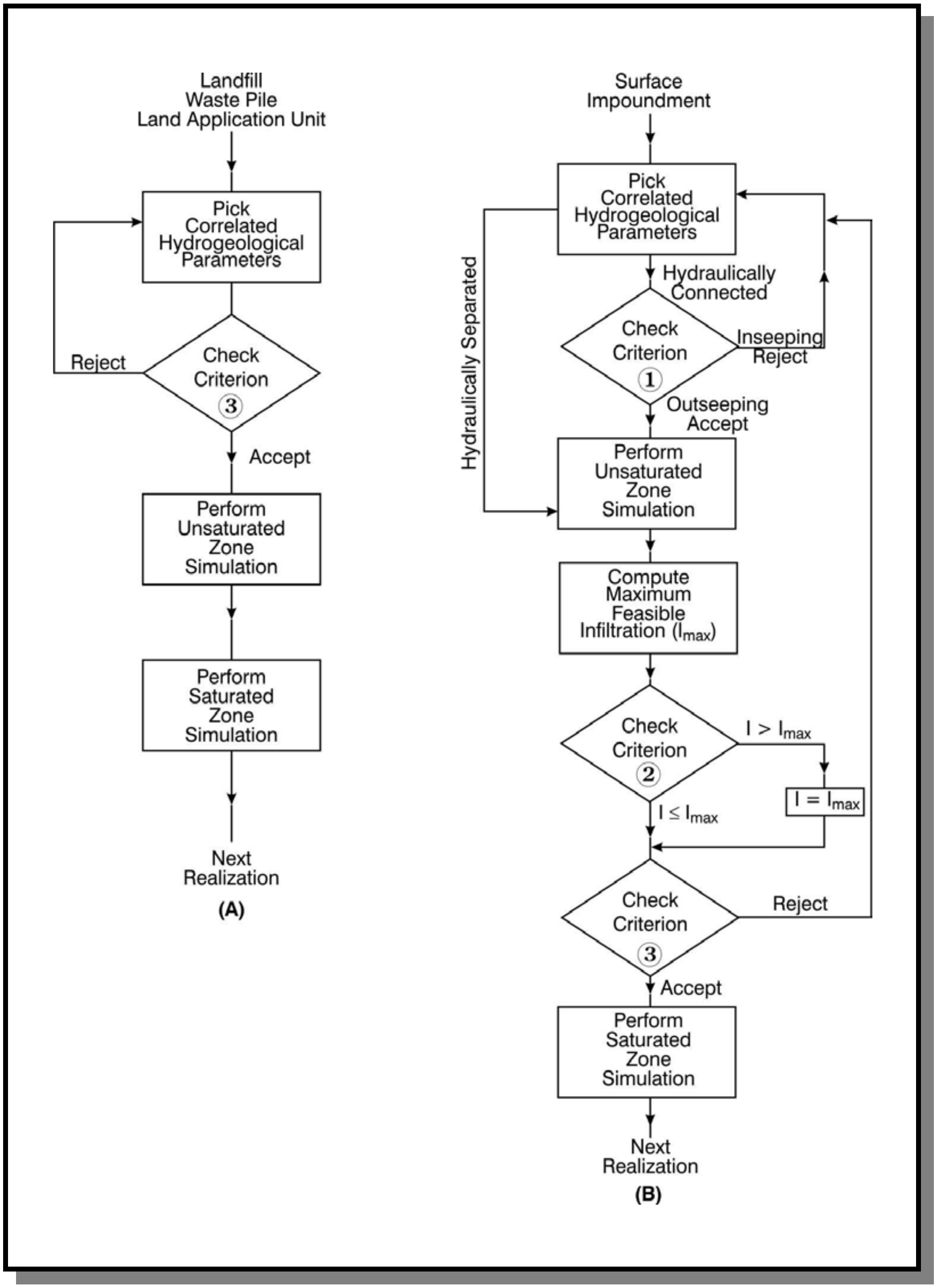

Figure 4.11 Flowchart Describing the Infiltration Screening Procedure.

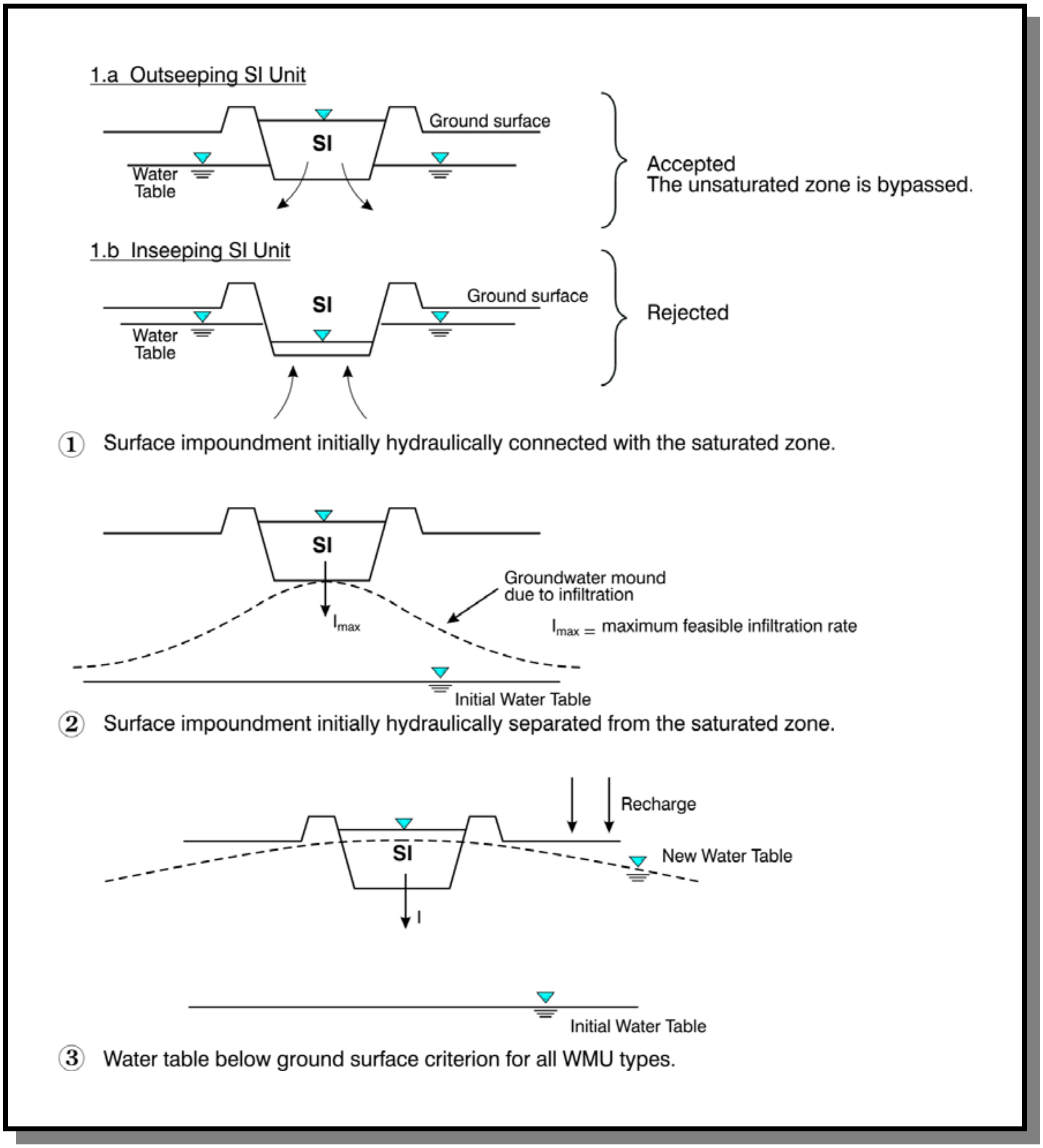

Figure 4.12 Infiltration Screening Criteria.